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13. ABSTRACT (Maximum 200 Words) The purpose of this project has been to develop a small hand-held self-contained battery powered diagnostic ultrasound (US) unit that would be highly transportable and relatively easy to use in the context of combat casualty care. The primary goal is to decrease the incidence of exsanguination on the battlefield secondary to intra-abdominal bleeding (hemoperitoneum) from blunt abdominal trauma (BAT). The scope includes telemedicine capability allowing remote diagnosis and direction as needed by a medic in the field using a variety of transmission modes (satellite to Internet). This has resulted in the development of a DARPA prototype unit, and a commercially available hand-held self-contained diagnostic ultrasound unit (SonoSite 180) weighing about 5 lb. and having telemedicine capability. Evaluations by experts have rated the unit to have good diagnostic image quality similar to a mid-range clinical diagnostic unit. The ability to get a good quality sophisticated portable US unit to the soldier/patient in a remote setting regardless of location, and to be able to transmit the image to an expert for remote diagnosis as needed, is of major significance in triage evaluation.				
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## INTRODUCTION

*This project involves the development of a sophisticated portable digital hand-held diagnostic ultrasound (US) system with telemedicine capability for combat casualty care. The primary goal has been to provide diagnostic triage at forward echelon levels in order to decrease the incidence of exsanguination on the battlefield. The main focus has been detection of internal bleeding from blunt abdominal trauma (BAT). The hand-held ultrasound unit (HHU) can be carried by a medic, incorporated into the 'Trauma Pod', HMMV, CSH, and with FAST units.*

The cooperative effort between DARPA/USAMRMC, the University of Washington, and three major corporations (Advanced Technology Laboratories (ATL), Harris Semiconductor, and VLSI Technology) resulted in the development of an easy to use high quality self-contained battery powered US unit using ASIC's (application specific integrated circuits) weighing about 5 lb. (including batteries). The diagnostic quality and added benefit of color 'power doppler' for visualizing blood vessels along with telemedicine capability allowed the project to significantly exceed the original goal of detecting internal abdominal bleeding (hemoperitoneum). Some of the additional diagnostic capabilities include gall bladder and kidney stones, appendicitis, fractures, thoracic trauma, cardiac tamponade, detection of foreign bodies (including plastic), vascular bleeding and disruption, and ectopic pregnancy. The telemedicine capabilities have expanded the diagnostic capabilities both by allowing remote experts to aid in diagnosis and in the ability to remotely direct the US examination when needed. We now have the ability to get the diagnostic unit to the soldier/patient (rather than the patient to the unit) and to get the diagnostic information to the expert when needed regardless of location. Telemedicine and compression with video codecs has been successfully tested including sophisticated satellite (using the ACTS mobile terminal (AMT) developed by NASA), ISDN phone lines, the Internet, and POTS (plain old telephone service). Specific techniques of compression (including wavelet) have been developed and tested. Clinical protocols have been developed for remote diagnosis for a number of clinical applications for use with and without telemedicine extending from novice to expert levels.

## **BODY**

**DAMD17-97-1-7258**  
**TELEMEDICAL PORTABLE ULTRASOUND**  
**(TELEMEDICINE-REMOTE PORTABLE ULTRASOUND)**  
**UNIVERSITY OF WASHINGTON DEPARTMENT OF RADIOLOGY**  
**Concise Statement of Work: 1 June 1997 through 30 September 1999**

### **Task 1 - Human Factors Questions**

*Testing of remote direction and diagnosis of portable ultrasound examination in the tele-ultrasound laboratory.*

#### **Remote Direction: Ultrasound Examination for Abdominal Trauma**

The primary function of the ultrasound laboratories is the assessment of direction and diagnosis of a remotely performed ultrasound examination. Ultrasound laboratories were established in two sites: 1) the clinical ultrasound department in the Department of Radiology at the University of Washington Medical Center (SW206). 2) in a research area in the Radiology Department (SS-232D).

The majority of the testing was performed with an ATL UM-4 and the DARPA C-60 prototype. Various types and frequencies of scanheads were employed with the majority of scanning performed with a general purpose 3 MHz mechanical sector scanner with a medium focus depth (5-9 cm) for abdominal evaluation. Time gain control (TGC) was set for an average male abdomen, dynamic range average 47-58 dB, depth 160 mm - 210 mm, power 20%-84%. Scanning was performed on normal male volunteers by personnel ranging from a level of no previous ultrasound experience to highly trained and skilled sonographers including radiologists specializing in ultrasound. The examination was controlled and monitored by radiologists with expertise in performing and diagnosing ultrasound examinations. The laboratory sessions were videotaped. In addition to laboratory testing, field tests were performed in remote settings with direction from radiologists at the University of Washington Medical Center using two-way video and audio via the ACTS Mobile Terminal (AMT) via satellite, earlier in the project.

In the ultrasound laboratory three basic scenarios were used. Lab protocols refined to test three basic modes: 1) direct remote from ultrasound (US) image only, 2) direct with observation of patient, scanhead, and US image, 3) direct remote using US image and TV image of patient and scanhead. In addition, testing was also performed with the use of head mounted display (HMD) goggles which were used 1) with the person doing the examination, 2) with the radiologist directing the exam.

The ultrasound examination focused on the abdomen with emphasis on evaluation of blunt abdominal trauma (BAT) as would be experienced in a combat triage setting. Initial efforts with inexperienced personnel concentrated on the right upper quadrant (RUQ) with identification of the liver and right kidney and the region of Morison's Pouch (the area between the liver and

kidney which is a common location of blood in the abdomen). The examination progressed to include the left upper quadrant (LUQ) with identification of the left kidney and spleen. The remainder of the abdomen was eventually added, including the bladder and region of the Pouch of Douglas(a common site for abdominal fluid to collect). Gross cardiac assessment, to rule out pericardial fluid etc., and diaphragm to rule out intrathoracic as well as intra-abdominal fluid was eventually included (see protocols).

Information was obtained in the laboratory sessions in terms of the instructions and choreography necessary to direct the remote examination. Several factors became apparent. A standard set of terms for direction is a prerequisite to consistency and speed. A glossary is being compiled and added onto. Some key standard terms have been developed e.g. point, angle, rotate, sweep, etc. We discussed the merits of using the words 'point' and 'angle,' and observed that 'point' might be more intuitive, because it inherently refers to where the ultrasound beam is being "pointed" as opposed to being somewhat vague about which transducer angle, which might be the back angle, rather than the forward pointing angle of the transducer. The phrases we used were:

- point towards the head
- point towards the feet
- point towards the left
- point towards the right
- point towards the left shoulder
- point towards the right shoulder

Another command we found useful was 'rotate,' as in rotate the arrow towards the right side and this implies a rotation in that direction, stopping so that the arrow points towards the patient's right side. This is a rotation around the axis of the transducer, and the 'arrow' is synonymous with dot and line. We discussed having the transducers marked with a visible, and perhaps also palpable, arrow, because it would be easier to explain to individuals operating with little training in difficult environments.

Another good command is 'move,' as in move the transducer one inch towards the head and we discussed the possibility of using metric measures instead of English, but decided that English might be better.

We must stress in the training process that all of these motions should be slow, because the video will de-correlate at all but the very highest data rates if quick movement are performed. The slow movement also allows the remote physician to monitor the course of the action, and stop it if it is going in the wrong direction, goes past the desired point, etc.

While we used 'point' in the sense of making a one-time change of approximately twenty degrees, which might be repeated, we used 'sweep' to describe the same type of motion, but continuous until the physician asks that the sweep stop. Most operators will have a tendency to stop automatically as the transducer approaches the position of being parallel with the abdomen, since they will observe that the ultrasound beam would be pointing outside the patient with a full (90 degrees) sweep from a mathematically normal angle (pointing into the patient at 90 degrees). The sweep should always be slow. The terms we used included:

sweep to the patient's right  
sweep to the patient's left  
sweep anteriorly  
sweep posteriorly  
sweep superiorly  
sweep inferiorly

Ideally the vocabulary is developed using a set of terms which are natural to both the medic and radiologist and do not require a great deal of specific definition for either user group.

In terms of training, we were surprised and pleased at how quickly untrained personnel were able to be directed in a successful abdominal ultrasound examination with remote instructions by the radiologist. A military medic with basic knowledge of abdominal anatomy should learn even more rapidly.

In examining the requirements for directing a remote scan, we found that one area of vital importance was the amount of training which the medic or other field personnel had received, and what skills we could count on in the field. Initially, we were viewing the environment as one in which a relatively naive user would be asked to assist in performing the examination. As we discussed the situation with more individuals, we were led to believe these field users would have specialized training in the mechanical aspects of the operation of the equipment, such as unpacking the device from its field container and positioning of the hardware and antenna. We now believe that it will be possible to have these individuals trained with a modest amount of ultrasound scanning experience, including the nomenclature of transducer positioning, as well as recognizing basic anatomy on the image.

Therefore, we now view our task as to not only develop the procedure, but also an outline of a training program for the field personnel, to include recognizing basic anatomic landmarks, and how internal organs look on ultrasound exams. The training could be added to the basic medic training and be expected to be included in several 1-2 hour segments over a 2-3 week course. This amount of training will be within the scope of training normally provided to medics by our military services. This will be further refined and tested as the project continues. Along with identification of abdominal fluid (hemoperitoneum), organ contour and detail will be added to aid in detection of the bleeding source. A standard examination is described under the section entitled "Protocols".

Another factor which became apparent with satellite testing is the need to hold the transducer relatively still when organ detail is needed. This is related to the compression ratios employed with the codec's (see white paper compression factors). Although localization can be performed with a relatively rapid movement of the transducer, the medic will have to be trained to decrease the rate of movement of the ultrasound scanhead when optimum anatomic detail is needed.

The approximate two second delay experienced with field testing with the ACTS satellite did not appear to pose significant difficulty. The delay was most obvious with the audio component and could be adjusted to with relative ease. The control of equipment will need additional work as the miniaturized hand-held unit is developed but appears to be best mitigated by simplification and standardization of the controls. At this point it appears that a single transducer in the 3 MHz

range with a mid-range focus should suffice for the great majority of soldiers. A variable frequency single transducer with a simple near or far, or large or small, setting could also be considered. Standard settings for dynamic range, depth, power, etc. could be used to allow a minimum of operator equipment function. Color Doppler or Power Angio capability could be added when needed for vascular diagnosis at the push of a button.

The question whether to use both a TV video image of the patient and scanhead position (scenario #3) or whether the examination can be satisfactorily performed with the ultrasound (US) image alone (scenario #1) will need further testing and evaluation. Although it appears the US image alone may suffice there are instances where the TV image of the patient could be helpful. This may be best added as a toggled insert (picture-in-picture) in the ultrasound image. The use of head mounted devices (HMD) will also be a factor in the incorporation of the imaging system. All of these issues will be further evaluated as the project develops.

Note: the diagnostic testing results are included in Task 6 – Clinical Evaluation: Controlled Conditions.

*Continue ultrasound unit protocols development and recommendations. Additional diagnostic procedures will be evaluated and added to existing protocols, e.g., pneumothorax, fracture.*

#### PROTOCOLS: Remote Ultrasound Evaluation

Basic ultrasound (US) scanning protocols were developed and tested in the laboratory on normal volunteers. The protocols for assessing abdominal trauma in a battlefield setting were primarily established by Dr. Shuman who chairs the American College of Radiology Committee on abdominal trauma, Dr. Carter (radiologist, principal investigator), and with input from Dr. Schmiedl who has had significant experience both performing and evaluating abdominal trauma with ultrasound in Germany and the United States.

Extensive review of protocols used in Europe, Japan, and the United States [Ma95, Roth93, Rozy93, Kimu91, Fors92] were performed, along with the results obtained, so as to be consistent with existing criteria and to avoid 'reinventing the wheel'. Ultrasound evaluation of blunt abdominal trauma has been established as a diagnostic procedure in both Europe and Japan for a number of years being primarily used by surgeons to determine the presence of abdominal blood (hemoperitoneum) or fluid. The primary emphasis has been on the detection of fluid rather than determination of the bleeding source. The overall accuracy rate for detection of abdominal fluid has been in the 90% range while the detection rate for organ damage has been considerably lower (40-75%). As the patients have been evaluated with US in a hospital setting, the presence of fluid has been used as the criteria for surgery. In a battlefield setting it would be valuable to know the bleeding source (usually spleen, liver, or kidney) for triage as well as the presence of fluid.

The evaluation of organ trauma was incorporated into the criteria, which are included as this can be crucial in battlefield triage management. Two additional factors which affect remote US scanning protocols are: 1) the changing clinical management of abdominal trauma which is for less surgery and more observation with non-surgical management, 2) the additional sophistication of ultrasound equipment which includes color vascular capability. The added

dimensions of telemedicine and hand-held portability are also factored into the proposed protocols.

Two somewhat different sets of protocols are included for blunt abdominal trauma. It was elected to not combine these at this point until further testing and refinement occur with additional testing in real trauma settings which are planned for both Harborview Medical Center (HMC) in Seattle, and Madigan Army Medical Center (MAMC)/Fort Lewis, in Tacoma, WA. Additional temporal i.e., serial protocols, will also be added e.g., scanning intervals of 2 x 5 minutes, 2 x 10 minutes, and 2 x 20 minutes depending upon the clinical signs and symptoms and the US findings. These will be incorporated with standard 4/5 quadrant protocols as presented on the following pages. Additional protocols are also planned for evaluation of vascular injury and shrapnel detection along with other scenarios which may occur in a deployed setting.

Note: A 5 quadrant abdominal trauma survey was demonstrated (approximately 2 minutes) for Col. Richard Satava while he was visiting the University of Washington. This included the 4 quadrants of the abdomen, cardiac assessment, and evaluation for intrathoracic and intra-abdominal fluid and organ trauma.

#### PROTOCOLS Ultrasound Scanning - remote Blunt Abdominal Trauma (battlefield environment)\*\*

*Basic four (4) position survey (2-3 min.)*

##### I. Epigastrium - *begin transverse*

- 1) global cardiac function
- 2) pericardial fluid
- 3) liver - evidence of trauma or fluid
- 4) longitudinal - same as above

##### II. Right Lateral - *begin longitudinal*

- 1) liver, right kidney
  - fluid in Morison's pouch (between liver and R kidney)
  - fluid around liver, kidney, paracolic gutter
  - evidence of trauma to liver\* or kidney\*
- 2) right diaphragm
  - fluid - intrathoracic, intra-abdominal
  - motion
- 3) transverse
  - right lobe of liver"
  - paracolic gutter

### III. Left Lateral - *begin longitudinal*

- 1) spleen\*
  - evidence of trauma or fluid
- 2) left kidney
  - evidence of trauma, or fluid
- 3) left diaphragm
  - fluid - intrathoracic, intra-abdominal
  - motion

### IV. Suprapubic - *transverse 6 longitudinal*

- 1) bladder contour, volume
- 2) fluid in pouch of Douglas

\* Use color as indicated, i.e. abnormal contour, disruption, density or evidence of trauma.

\*\* Using interactive telemedicine

### Right Upper Quadrant (RUQ) Pain\*\*

*Note: Survey varies whether history of trauma*

1. liver\*
  - longitudinal and transverse
  - biliary ducts, contour, echo pattern
2. gall bladder - note size
  - stones
  - wall thickness
  - fluid collections
3. abnormal fluid collections
  - Morison's pouch
  - paracolic gutter
  - other
4. diaphragm
  - motion
  - fluid, above (intrathoracic), below (intra-abdominal)
5. right kidney\*
  - hydronephrosis
  - motion
  - evidence of abnormal contour or trauma
6. presence of foreign bodies metallic and non-metallic

**\*\* Using interactive telemedicine**

**\*Use color as indicated (trauma)**

### R/O Kidney Stones\*\*

1. longitudinal and transverse of both kidney

*examine symptomatic (pain) side first*

- note presence of hydronephrosis (dilated collecting system)
- look for presence of echogenic calculi (stones)
- note abnormal fluid collections

2. follow general course of ureters

- note dilatation
- echogenic calculi

3. bladder

- volume
- ureteral jets\*

4. presence of foreign bodies or masses

**\*\* Using interactive telemedicine**

**\*Use color as indicated**

### Ureteral Jets

Note: The use of 'ureteral jets' as a screening method for urinary obstruction is proposed. This should be performed with a full bladder if possible. With the portable US unit (SonoSite 180) set in the color power angio mode the bladder is visualized in cross section (transverse). Both the right and left 'ureteral jets' should be observed (posteriorly) in the normal patient. Non-visualization on the symptomatic side is suggestive evidence of obstruction. Further evaluation (above) can then be performed.

### Abdominal Trauma

Steps for ultrasound scanning by trained personnel in trauma (battlefield) environment - assuming direct interactive communication with radiologist or other professional during scanning.

If the patient can hold their breath:

1. Scan in the longitudinal plane during deep inspiration starting in the right posterolateral subcostal region and moving toward the left, passing to the right posterolateral subcostal region. Move slowly. Stay subcostal during entire right-to-left pass. Observe for:

1. fluid in the right and left pleural space
2. fluid superior or inferior to the liver
3. fluid inferior or superior to the spleen



4. Any free fluid
  5. Evidence of fracture or hemorrhage in the liver or spleen
2. Scan between the right lateral 8-11th ribs posterolaterally and anterolaterally during deep inspiration. Mover back and forth in the rib interspace. Tilt the transducer up and down in the interspace. Observe for:
1. Free fluid in pleural space
  2. Free fluid around liver
  3. Evidence of fracture or hemorrhage in the liver.
3. Scan between the left lateral 8-11th ribs posterolaterally and anterolaterally during deep inspiration. Mover back and forth in the rib interspace. Tilt the transducer up and down in the interspace. Observe for:
1. Free fluid in pleural space
  2. Free fluid around liver
  3. Evidence of fracture or hemorrhage in the spleen.
4. Scan transversely in the right and left axillary lines moving from the subcostal space to the iliac crests. Observe for:
1. Free fluid around the colon or among loops of bowel.
5. Scan longitudinally midway between the umbilicus and the right and left iliac crests. Observe for:
1. Free fluid around loops of bowel.
6. Scan longitudinally and transversely on midline just above the symphysis. Observe for:
1. Free fluid posterior to the bladder or around rectum.

If the patient cannot hold their breath:

Scan as above except scan steps 1-3 with the patient breathing.

### Pneumothorax

Current studies and research are using ultrasound as an alternative to diagnosing pneumothorax. This is particularly useful in remote settings such as the battlefield where conventional x-ray methods may not be available.

The US is best performed with higher frequencies (3 MHz or greater) with near field focus in the upper thorax (e.g. 2<sup>nd</sup> or 3<sup>rd</sup> anterior intercostal spaces). It is important to visualize both the right and left chest for comparison. The normal side should show visualization of both layers of pleura, i.e. parietal and visceral. There should be a sliding motion of the visceral pleura (lung) with respiration. The loss of visualization of both (2) layers of pleura and the 'sliding' motion is suggestive of pneumothorax.

Ultrasound (US) should be placed in the superior intercostal spaces and respiratory motion of the pleural surfaces noted with comparison of the right and left sides.

## Fracture

Ultrasound (US) can be used to identify fractures, particularly in long bones and extremities. The US can identify the disruption at the fracture (Fx) site and the angulation and distraction of the fracture fragments. The US also has the advantage to evaluate the soft tissue changes, including hematoma and periosteal elevation.

The US examination should include longitudinal and transverse views at the fracture site. Motion views can also be helpful. US examination should include areas proximal and distal to the fracture. Vascular structures should also be identified and compared with the normal side to evaluate relative flow and structure.

## Shrapnel

Evaluate the area where shrapnel is suspected in multiple planes with varying levels of gain and focus. The shrapnel should produce an echogenic area with acoustic shadowing. (See Appendices.) The adjacent blood vessels should also be evaluated using the power angio setting.

## Vascular Injury

The hand-held ultrasound unit (HHU) is set on the power angio mode. The vessel at the site of injury is evaluated in longitudinal and transverse axes. Disruptions in the wall, narrowing, or decreased flow are noted and compared with the opposite when applicable.

## Cardiac Tamponade

The heart is visualized from the substernal/epigastric approach in at least two views and from the anterior intercostal approach when possible. An abnormal fluid collection surrounding the heart is suggestive of cardiac tamponade. There may be decreased cardiac pulsations along with the pericardial fluid/blood.

*Specifications and design requirements for the ATL hand-held ultrasound unit. In conjunction with ATL and the military (Brooke Army Medical Center, Lackland AFB, San Diego Naval Hospital, and Madigan Army Medical Center), define user interface needs for controls, image display, transducer, color vascular capability.*

Device Requirements/System Design/Human Interface Review  
Clinical Diagnostic Application and Design Parameters  
(Sonologist-hospital: Sonographer-remote in field)

## **Combat Casualty Care:**

**Primary Application:** detection of internal bleeding from abdominal trauma. Detection of intra-abdominal blood (hemoperitoneum) or fluid, assessment of bleeding source (organ damage) when possible.

Additional applications: organ trauma (including liver, spleen and kidneys), bladder trauma, gall bladder, appendix, kidney stone, vascular integrity and flow, cardiac activity and tamponade, pleural effusion, and shrapnel detection.

**Device Size:** ideal hand-held portable 'pocket size' would be optimum.

**Controls:** simplify yet flexible

- retain capability of basic input and output gain(? combine in one)
- Need depth (focus) and timed gain control (TGC)? whether can be combined and simplified into e.g. small, medium, large size patient.

**Display:** Flat screen LED or FED size approximately 5" (diagonal) seems to be adequate for viewing and resolution 360 x 480 (sharp?) appears adequate to clinical observers (radiologists and sonographers) however is very viewing angle dependent and can use more brightness in bright daylight. FED may be better on both aspects. Note: a brightness control with a photocell may be helpful to adjust for varying brightness levels.

Night time application would be best with lower light levels or head mounted device (HMD) goggles.

**Transducer:** Size and shape are important for resolution and access. A smaller transducer allows intercostal access which is often helpful for the detection of abdominal fluid particularly in the region of Morison's Pouch between the liver and right kidney which is a common area for blood or fluid to collect. Some compromise occurs between size for access and resolution as the larger proposed curvilinear 96 element transducer offers better resolution at 60mm than at a small size which would allow improved intercostal access. This may necessitate some modification.

**Telemedicine:** This is presented in a separate report by Stewart and Carter. The hand-held unit will offer satellite NTSC video, telephone, and internet telemetry capability. 2-way telemedicine will often be crucial in the direction and diagnosis of a successful examination. This will allow expert medical consultation by a subspecialist ultrasound expert as needed by the remote operator in the field.

**Sterility:** A method of keeping the unit as sterile as possible and avoiding transfer of blood from patient to patient will be necessary. This may be accomplished with sheathing of the transducer portion of the unit or providing an easily cleaned scanhead.

**Spatial Design:** The placement of controls is important for ease of use. A detachable 'scanhead' appears to allow the most flexibility.

Whether it is best to place the controls with the transducer or the power/display portion can be further evaluated in terms of ease of use, sterility, etc. A means of operating the unit with the transducer attached also would facilitate one handed operation when necessary in the field.

**Clinical Modes:** It is desirable to have both real-time and static capability. Color vascular capability is also desired. It appears color power angio (CPA) will be provided for color vascular evaluation. Doppler may add value as a later option. A form of 'hand-sweep' 3D capability will also provide additional diagnostic capability.

*Videotape tele-ultrasound sessions with semi-portable equipment. Analyze videotaped sessions and determine requirements (mock-up of hand-held unit).*

Videotape (S-VHS) Ultrasound (US) sessions were performed with the ATL UM4 and the DARPA C60 prototype units. These were performed with and without telemedicine at variable transmission rates, (see Tasks 3 & 5) and with and without compression at variable rates (see Task 3).

Both live 'normal' subjects and S-VHS videotaped material from volunteer subjects were used. A wide range of anatomy was evaluated. The primary focus was on the abdomen with the emphasis on ruling out abdominal trauma with the detection of intra-abdominal fluid (hemoperitoneum). Additional anatomy was included for evaluation of anatomical detail including vascular, cardiac, pregnancy, thyroid, and evaluation of 'ureteral jets' in the bladder using color power to evaluate urinary obstruction from 'kidney stones'. Organ vascularity was also evaluated using the color power Doppler US.

Remote US scanning using telemetry was analyzed with the level of expertise at the remote site ranging from novice to expert, and the receiving site having a radiologist with expertise in US for diagnosis and direction. The system had the ability to do 2-way audio and video. Tests were performed and analyzed (see Task 6-Clinical Evaluation) using 2-way audio and video both with and without images of the patient and scanhead position. There was always transmission of the ultrasound (US) image. The value of the image of the scanhead/patient was noted to vary depending on the skill of the participants (see results Task 6).

The LCD screen size (5" diagonal) and image quality of the DARPA C60 were thought to be comparable to the ATL UM4 (a mid range unit). There was noted to be a significant increase in diagnostic quality going from 256 kbps to 384 kbps. Slow scan video (1-3fps) was also satisfactorily (i.e. both direction and diagnosis) demonstrated on the Internet. Both an NTSC video output and PCMCIA connection were recommended for the hand-held US unit.

*Portable ultrasound unit protocols and recommendations for the battlefield.*

The portable hand-held US units (both the DARPA C60 prototype and the SonoSite 180) were found to be comparable in terms of diagnostic quality and application to the mid-range ATL UM4. Because of this, the protocols developed during the testing with the semi-portable UM4 did not require significant modification.

The 'ureteral jets' evaluation (see Protocols) was added as a means of assessing urinary obstruction because of the addition of the 'power angio' capability of the hand-held unit. This

relatively simple screening method should be able to be performed by the medic in the field after training.

An additional area that was added was detection of shrapnel. US has the advantage over standard x-ray in that it can be used to locate radiolucent materials such as plastic which is often contained in land mines (see Appendices).

## **Task 2 - Testing with the Advanced Communications Technology Satellite and MIL COM**

*Further field testing with AMT as budget allows, including anticipated higher data rates.*

Additional field testing with the ACTS AMT was not performed for two reasons. 1) The budget did not allow for the significant expense that had increased to \$10,000 - \$20,000 per week with increases in charges from JPL/NASA. 2) The portable self-contained battery powered unit (SonoSite 180) was not available until September 1999 which did not allow adequate time for field testing.

Note: The previous extensive field testing with the ACTS AMT is included in the Appendices and Task 3.

## **Task 3 - Real-time Video Compression Factors**

*Obtain extended US video clips and compress using codecs at various bandwidths. Radiologist preference testing using the px64 compression algorithm with Likert scale/Kappa statistical analysis. Wavelet real-time video image compression algorithm (as equipment budget allows).*

### **MPEG Compression of Collected AVI Video Clips**

We used the Data Translation Broadway MPEG video codec to capture direct NTSC video and S-VHS videotape sequences to computer disk. It was much more convenient and scientifically valid and reproducible to directly capture the digital compressed video stream and play these back via PCs to the radiologists for the Likert evaluation, rather than from videotape.

As the MPEG standard has at its roots many of the same intraframe and motion vector compression algorithms as the H.261 (such as that used in the Harris Narrowband Video Codec that was demonstrated with previous ACTS/AMT experiments [Stew95, Stew96, Stew97]), we used the MPEG compressed video sequences (.mpg files) to best gauge what minimum bandwidths are necessary for clinical detection of trauma on the battlefield. We also used the Broadway board to collect losslessly compressed (.avi file) video clips (from which the MPEG files are derived) from high quality S-VHS tapes for imaging exams performed in the clinic. The MPEG files were then created at specified playback bandwidth (with associated compression ratio - see Tables I and II) using the Broadway MPEG-1 hardware video codec.

A priori compression ratios were established to provide a given output bit rate (128, 256, 384, 512, 768 and 1544 kbits/second). These compressed video clips (and an original with no lossy compression - .avi) were then played back for the observing radiologists who then answered the

appropriate Likert evaluation questions for the given anatomy/pathology visualized in that videoclip (see section III, Likert Evaluation using Kappa Statistics, below).

### Status of Wavelet Compression

Although we were to have received on 15 August 1997 the Videowave PCI Wavelet compression card from Quadrant International, Inc., further production delays made this board unavailable for this project. We did however, purchase the Momentum ADV601 VideoLab PCI board which was used in for wavelet-based video compression and was housed in the VA Research Windows95/Linux PC purchased for compression work under this contract.

The ADV601 Videolab board is sold as an experimental board to assist design engineers in making quick and easy use of the Analog Devices ADV601 Codec. This board is not intended for consumer use or use by persons without the technical knowledge to write their own software and design their own hardware. With the addition of a post-doctoral fellow (Rex Andrew, Ph.D. started in our laboratory on 1 September 1997) to help develop the interframe and network videostream wavelet application on this development board set, we were able to compress in real-time the incoming video (and eventually digital estimate data stream - the first prototypes of the hand-held unit will not have a digital output interface, but a digital interface for the production version is now under discussion) from the hand-held unit.

The minimum observed compression rate for the ADV601 Videolab is 6:1 and the maximum is 350:1. To fully digitize CCIR-601 video (720x480x30fps, 4:2:0 format) requires 162 Mbps. Tables I and II below indicate required compression ratio versus network link bandwidth and frame rate. To show CIF (common intermediate format) resolution (352x288) at 384 kbps (becoming a telemedicine standard minimum bandwidth) requires a compression ratio of 105:1 at 30 fps, but only 26:1 at 7.5 fps. Thus the ADV601 Videolab worked nicely for the application.

Table I. Compression Ratio Versus Bandwidth

Bandwidth at 30 fps	CIF Comp. Ratio (wrt CCIR 601)	QCIF Comp. Ratio (wrt CCIR 601)
T-1 (1544 kbps)	27:1 (108:1)	7:1 (108:1)
3 BRI (384 kbps)	105:1 (432:1)	26:1 (432:1)
2 BRI (256 kbpsP)	158:1 (648:1)	40:1 (648:1)
1 BRI (128 kbps)	316:1 (1296:1)	79:1 (1296:1)

Table II. Compression Ratio Versus Frame Rate

Frames per second (fps)	CIF Comp. Ratio (wrt CCIR 601)	QCIF Comp. Ratio (wrt CCIR 601)
3.75	13:1 (432:1)	3.3:1 (432:1)
7.5	26:1 (432:1)	6.6:1 (432:1)
15	53:1 (432:1)	13:1 (432:1)
30	105:1 (432:1)	26:1 (432:1)

Final results for the wavelet real-time video compression algorithm can be found in the two articles by Andrew, et al.: "Wavelet Compression of Ultrasound Video Streams for Teleradiology

(attached)” and “A 3-D Wavelet-based Codec for Lossy Compression of Pre-scan-converted Ultrasound Video (attached).”

## Likert Evaluation using Kappa Statistics

### A. Likert Evaluation

A five point Likert [Meet88, Merr94] scale was used to gauge the viewers impression of the diagnostic quality of the MPEG compressed video clips. For each videoclip selected for the study, the readers (board-certified ultrasound radiologists) assessed specific, key diagnostic features on a scale from 1-5 (see Table III). An example of the key feature questions addressed to the readers for the MPEG videoclip of the right upper quadrant (RUQ, liver-kidney boundary = Morisons pouch) presented in Figure 1 are given in Table IV.

Table III. Five point Likert scale ratings.

Likert scale rating	Specified feature diagnostic quality
1	No useful diagnostic information
2	Some grossly useful information
3	Fair diagnostic quality
4	Moderate diagnostic quality
5	Good diagnostic quality



Figure 1. Right Upper Quadrant MPEG compressed ultrasound videoclip at 1544 kbps playback bandwidth (30 fps).

Table IV. Right Upper Quadrant: video compression key feature Likert evaluation questions.

1. Visualization of kidney and liver contours?

2. Fluid visualization (i.e., can R/O significant fluid and blood in Morisons pouch)?
3. Normal respiratory motion?
4. Comparative echogenicity (i.e., liver > kidney)?
5. R/O hydronephrosis?
6. R/O dilated biliary ducts?
7. R/O renal or hepatic fracture?

## B. Videoclip selection

Of the over 100 videoclips collected, only six were selected for the initial Likert evaluation. These videoclips of anatomy or pathology best representing the mix that might be expected to be found on the battlefield or in other military personnel situations. Table V lists the selected videoclips. Tables IV and VI through X delineate the key features to be extracted from the Likert assessment for each videoclip.

Table V. Videoclips selected for the initial Likert evaluation study with anatomy.

1. Right Upper Quadrant (RUQ)	kidney, liver, and Morisons pouch	Table IV
2. Abdominal Cross Section	pancreas, liver, aorta, inferior vena cava, splenic vein, renal vein, superior mesenteric artery and kidney	Table VI
3. Early Pregnancy	viable fetus, inter-uterine pregnancy (IUP), amniotic fluid, and yolk sac	Table VII
4. Aorta Cross Section	aorta	Table VIII
5. Aorta Longitudinal View	aorta, and superior mesenteric artery	Table IX
6. Testicular Trauma	testicle	Table X

Table VI. Abdominal Cross Section: video compression key feature Likert evaluation questions.

1. Overall anatomic detail
2. Pancreas visualization?
3. Liver visualization (portion included)?
4. Large vessel visualization (e.g., aorta, inferior vena cava)?
5. Other vessel visualization (e.g., splenic vein, renal vein and superior mesenteric artery)?
6. R/O dilated ducts?
7. R/O abnormal blood/fluid collection?

Table VII. Early Pregnancy: video compression key feature Likert evaluation questions.

1. Inter-uterine pregnancy (IUP) identified?
2. Fetal viability visualization (fetal heart motion, +FHM)?
3. Ability to estimate approximate fetal age?
4. Amniotic fluid within normal limits?
5. R/O abnormal blood and fluid collection and membrane separation (on this view)?
6. Yolk sac visualized?

Table VIII. Aorta Cross Section: video compression key feature Likert evaluation questions.

1. Aorta identified?
2. Aneurysm??



3. Dissection?
4. False lumen visible?
5. R/O abnormal fluid or blood?

Table IX. Aorta Longitudinal View: video compression key feature Likert evaluation questions.

1. Aorta visualized?
2. Celiac axis and superior mesenteric artery (SMA) visualization?
3. R/O aneurysm?
4. R/O dissection (on this view)?
5. Vascular pulsations?

Table X. Testicular Trauma: video compression key feature Likert evaluation questions.

1. Evidence of trauma?
2. Anatomical structure of testicle?
3. Evidence of fluid or blood?
4. Fracture lines or hematoma?

### C. MPEG Bandwidth (Compression) Selection

As was determined in the analysis of previous ACTS/AMT Likert descriptive and summation analysis [Stew96], there is a marked change in the MPEG and H.261 codec video quality going from 256 kbits/second (kbps) bandwidth (158:1 compression ratio ) to 384 kbps bandwidth (105:1 compression ratio). Note: the final results of the ACTS/AMT video compression work is given in the article by Stewart, et al. [Stew99]: "Application of the Advanced Communications Satellite to Teleradiology and Real-time Compressed Ultrasound Video Telemedicine (attached). Note: all of these MPEG compression ratios are generated at CIF resolutions (352x288); see Table I. There is a slow progression in video quality improvement from 384 kbps through the T-1 rate (1544 kbps = 27:1 compression ratio). The T-1 bandwidth video looks almost indistinguishable to the original, losslessly compressed AVI video clip, except for very minute and transitory blocking artifacts where the imagery changes discontinuously, as one would expect. Thus, we have decided for the initial Likert evaluation to use the 256, 384, 768 (half T-1) and the original AVI videoclips

### D. Web Interface

Because of the large number of permutations for the initial Likert evaluation (four bandwidths, six videoclips and an average six key feature questions per videoclip = 144 questions per session), it was decided that collection of paper records would be inconvenient and possible source of error. In addition, we sought a means of easy videoclip display and question answering to speed the radiologists through the Likert evaluation as quickly as possible, as it is very hard to get physicians to participate otherwise. Thus, we have developed a web browser interface using Microsoft Explorer 3.0 and Microsoft Front Page 97.

The web interface is shown in the following screen shots (Figs 2 and 3). After requesting the physicians to identify themselves and displaying a text section describing the Likert evaluation (Fig 2), the web interface allows the physician to play the videoclip by pressing a start button (fig 3). The usual videoclip movie controls (play, stop, forward, backward, etc.) are available for the

physician to interrogate the clip at their leisure. The Likert evaluation questions relevant to that specific video clip are displayed beside the videoclip and the rating from 1-5 is entered from the keyboard for each question (Fig 4). After answering the questions, the physician can then summon the next videoclip with associated questions, or return to the previous section. Physicians are allowed to replay and re-answer any videoclip until they close out the evaluation session, whereupon, the results are written out to a disk file, wherein they can be entered into an Excel spreadsheet for analysis using the Kappa statistical analysis described in the next section.

sgltest - Microsoft Internet Explorer

File Edit View Go Favorites Help

Back Forward Stop Refresh Home Search Favorites Print Font Mail Edit

Address C:\inetpub\wwwroot\us-eval2\sgltest.htm Links

**Introduction:**

This page will take you through a series of US images of varying anatomy and compression ratios. Please login with your full first and last name then press "Case 1". You will be directed to a case with the word "Start" underlined in blue. Clicking on it will launch the related video clip. Please evaluate the diagnostic utility of the clip by entering a number from 1-5 in the associated scoring fields. At any time you may move forward and back through the cases by pressing "Case N+1" or "Case N-1" (this assumes you are currently on case N). When you have completed all available cases, press "Done" at the end to write out a file containing your responses.

Please rate clinical image quality for the specified clinical feature using the 1-5 scale (5= best, 1= worst) for the following examples.

Last Name:

First Name:

Case 1

Figure 2. Front page of the Likert evaluation web browser: introductory notes and identification.

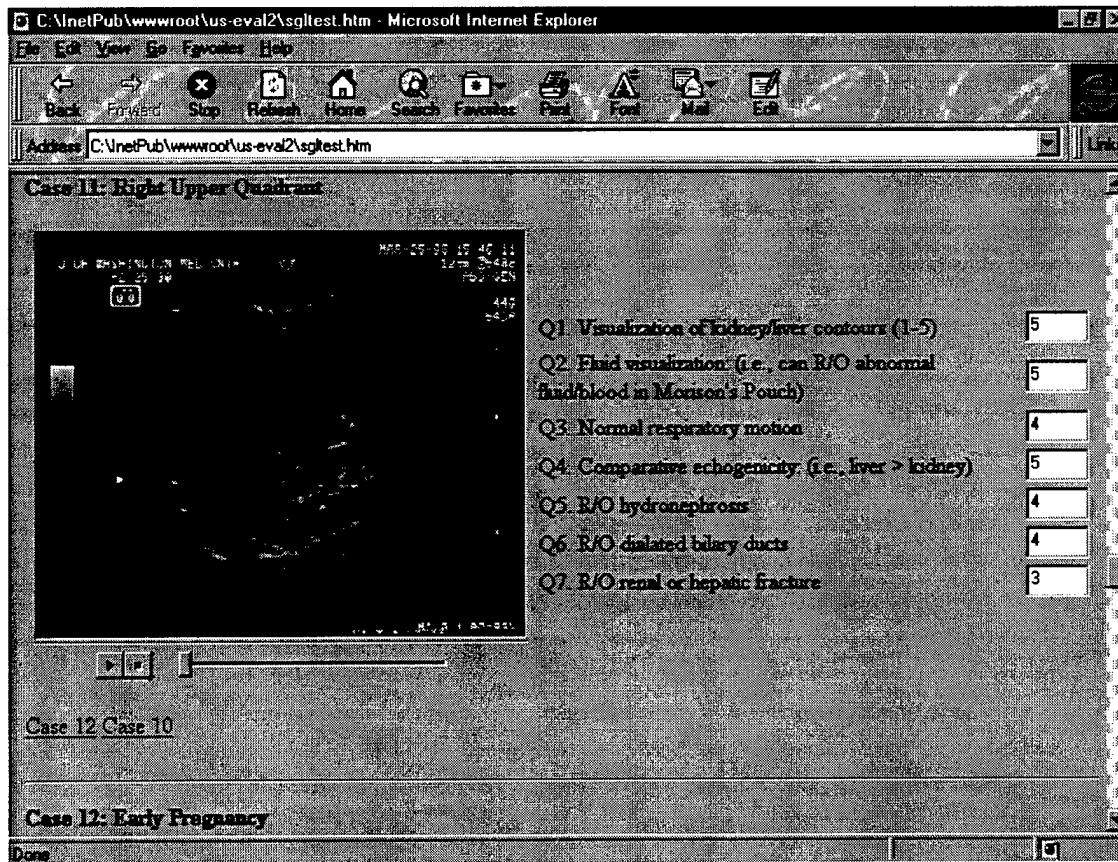


Figure 3. Videoclip display, control and associated key feature Likert evaluation questions.

#### E. Kappa Statistical Analysis

Kappa statistical analysis measures the degree of agreement between observers and between viewing assessment. Derivations of kappa statistics can be found in [Altm91, Flei81]. Herein, we restrict the presentation to the basic formulae employed in this study, first for two observers [Altm91], and then for more than two observers [Flei81].

The final results of the Kappa Statistical Analysis can be found in the article by Stewart, et al. [Stew98], "Compressed Ultrasound Video Image Quality Evaluation Using a Likert Scale and Kappa Analysis (attached).

#### Task 4 - Head-Mounted Display for Remote Direction/Consultation

*Head mounted display, video/audio transmission testing. Local and field testing and evaluation.*

#### INTERFACE CONSIDERATIONS

Clinical acceptability of the handheld ultrasound acquisition system will depend in large part on the adequacy of the human interface, for both the remote consultant and the field technician. Data displays must match the meaningful signal/noise ratio of the acquisition equipment,

communication bandwidth and modalities must be adequate and appropriate to the task, and the interface should ideally reduce the cognitive load of the task for both parties.

#### Remote Physician (consultant reading and/or directing ultrasound session)

Visual display requirements for the remote physician consulting with an on-site technician or medic may vary with the expertise and experience of the medic. Minimally, the remote consultant requires an ultrasound image of comparable resolution to the transmitted signal. For consultation with novice medics and for complex cases a video feed from an external camera (focused on the patient transduction site) may also be required. The optimal configuration of these monitors will depend on the current working conditions of the consultant. Ordinarily a workstation with two separate monitors should suffice, although human factors studies should be conducted to determine if some other configuration, such as picture-in-picture, is more effective. Head-mounted display should not be necessary unless the consultant is otherwise occupied, which is conceivable in certain combat or emergency response situations.

If the use of an external camera proves beneficial, then consultant control of the positioning of the camera may be desirable. Rather than relying on the technician in the field to position the camera while trying to acquire the signal, the remote consultant should be empowered to "look around" at will. Minimally tilt, pan, and zoom could be implemented with reasonably low overhead, as is currently done with some advanced remotely controlled "web cam" systems. Auditory input from the field should include a clear pickup of the medic's voice (not necessarily spatialized) and, in advanced systems, may also include auditory encoding of certain ultrasound signal features.

Additional data streams of potential use to the remote consultant might include: (1) eyepoint overlay of the medic's direction of gaze on the ultrasound image (perhaps as a small dot or reticule composited with the ultrasound screen image), which would provide essential information about the medic's focus of attention (Are we looking at the same thing?); and (2) the current spatial orientation and application pressure of the ultrasound transducer (either as a numerical readout or as a graphical display, such as an overlay on a virtual patient model). The latter data stream would require that the transducer be instrumented with pressure and 6D position sensors.

#### Field Technician or Corpsman

The field technician must be free to use both hands and to orient himself so as to see the patient. Since a tight coupling between kinesthetic feedback and visual feedback appears to be essential for effective ultrasound acquisition, the field technician must have immediate and continuous access to the ultrasound image, at real-time display rates. While proper placement of a stand-alone monitor is adequate within a clinic, field situations may benefit from alternative display methods, such as head-mounted displays (HMDs).

Head-mounted displays typically employ one of four image display modes: (1) fully occluded (in which the user's field of view is occupied by the image and surrounding blank space); (2) "see-around" (which places the occluded image display in only part of the visual field, allowing the user to see part of the surrounding environment while attending to the head-mounted monitor);

(3) "field-multiplexed" (which presents a small collimated occluded image monocularly within the open field of view, resulting in a perceived merging of the display with the surround); and (4) "see-through" (which allows the user to see the displayed image overlaid upon the surrounding environment, in traditional "augmented reality" mode).

Fully occluded HMDs are becoming more useful for this application, with techniques for including the surrounding environment, such as video capture and compositing, as discussed below. The total field of view of these displays, however, may be too limited for combat field use where peripheral awareness must be maintained. The weight and bulkiness of these displays, which heretofore were not clinically acceptable, have recently been reduced to more acceptable levels.

See-around HMDs are being used in a number of clinical applications. Two approaches have proven useful: (1) a device with minimal hardware surrounding the reflected image sources, which can be placed comfortably in the upper part of the user's field of view, affording a view of the user's hands and the patient in the lower field of view, and (2) a device with comparable spatial resolution and image size which can be positioned in either the upper or the lower part of the field of view (at the cost of some occluding hardware in the lateral periphery). We have successfully demonstrated the adequacy of the former device (the Virtual I/O glasses) for reading standard ultrasound studies (as judged by experienced ultrasound radiologists and technicians). Spatial resolution and form factor were determined to be clinically acceptable, although judgements about contrast resolution were more variable and warrant further study.

Field-multiplexed displays are exemplified by (1) the Private Eye (which occludes part of the field of one eye with a monochrome red image produced by a rapidly scanning linear LED array), and (2) the Virtual Vision Sport (which occludes part of one field with a full-color reflected video image). Both have adjustable focal length, but a slightly smaller field of view than the i-glasses. The clinical acceptability of these devices has not been assessed for this application, although similar devices have been incorporated into other field display systems with reasonable success. While certain of these devices which present only monochrome red imagery may be acceptable for other field applications, our pilot studies using these displays suggest that monochrome red displays do not have a perceptual dynamic range adequate for ultrasound reading.

See-through approaches hold considerable promise for this application, because they can accommodate the widest range of image placement options, including head-stabilized and patient-registered images. Unfortunately, most current image display methods do not have adequate brightness and spatial resolution to produce a fully saturated virtual image (resulting, instead, in a dim "ghosty" image in normal room lighting conditions and essentially no discernable image at all in bright sunlight). An alternative display method, the Virtual Retinal Display (VRD), is currently under development by our collaborators at the Human Interface Technology Lab. The VRD promises to deliver adequate brightness and spatial resolution for both occluded and see-through modes, in a lightweight and affordable unit. Unlike other HMD approaches, which rely on standard image sources, the resolution and dynamic range of the VRD are limited only by scanning and intensity modulation technologies. Using a novel mechanical resonance scanner the VRD currently produces VGA (and soon HDTV) resolution images. As

these devices become available as HMDs, we will assess their utility and usability for this application.

In addition to the ultrasound image itself, the field technician might often benefit from annotation overlays (on the image) generated by the remote consultant. Due to transmission delays in remote consultation, real-time overlays of live video may not be possible, but annotation of selected "snapshot" images is certainly doable with current technology. Alternative display methods should be explored, including presentation of annotated images in a separate window, or adaptive augmented reality overlay displays such that the position-dependent notations are displayed only if the transducer position is relatively stable. Since the remote consultant can thus point to the area of interest, there is no need for pointer registration on this end.

As for the remote consultant, clear voice communication is essential for the field technician. In our studies we have found that verbal instructions using a small set of conventions can be highly effective in directing an acquisition session, even with a novice technician. In addition, however, it may be advisable to explore the potential uses of (artificially) spatialized sound, which may require a special PC board to encode the user's head-related transfer functions (HRTFs) for real-time spatialization of monaural sounds. One might imagine, for instance, the consultant specifying an angle of orientation verbally, but having that command reinforced by emanating from the appropriate point in space relative to the technician or the transducer. Positioning of the virtual sound source could be controlled by the remote consultant via, for instance, a joystick. In addition, spatialized sound may be used to alert the combat medic to activity in the periphery that he may not be attending to adequately.

An additional emerging visual display technology is a form of augmented reality display called "shared space", currently under development at the Human Interface Technology Lab. In this paradigm, live video of the field of regard (from a small head-mounted camera) is processed by a local (possibly wearable) computer to identify the presence and location of a fiduciary marker. The live ultrasound video feed is then registered with the marker in the composited view through a head-mounted display. Thus, the ultrasound image display can be placed in any arbitrary position in the technician's field of operation, including on the patient or attached to the transducer. Our laboratory trials with the SonoSite 180 using this technique suggest that the "shared space" images are useful for a variety of ultrasound reading purposes (even at the reduced resolution of consumer level HMDs), and that the technique may provide an enhancement to the typical off-body placement of the ultrasound monitor. Future studies of this technique may be warranted, especially with anticipated improvements in spatial resolution of commercial head-mounted displays.

## **Task 5 - Stepwise Integration of the Target System**

*Communications requirements for the hand-held ultrasound unit.*

### **I. Connections from the hand-held unit to a base station or telecommunications connection.**

A. Could be one of the following:

1. Coaxial cable for connection of the RS-170 NTSC analog video output to an external monitor or analog video codec.

## **Wireless LAN**

In the last few years a new type of local area network has appeared. This new type of LAN, which is the wireless LAN, provides an alternative to the traditional LANs based on twisted pair, coaxial cable, and optical fiber. The wireless LAN serves the same purpose as that of a wired or optical LAN: to convey information among the devices attached to the LAN. But with the lack of physical cabling to tie down the location of a node on a network, the network can be much more flexible -- moving a wireless node is easy. As opposed to the large amount of labor required to add or move the cabling in any other type of network. Also going wireless may be a better choice where the physical makeup of the building makes it difficult or impossible to run wire in the building.

Wireless networks can be used in combination with cabled LANs. In that all the machines that will require relative mobility will be connected wirelessly, while the stations that are for the most part permanent can be connected through cable. Wireless LANs use one of three transmission techniques: spread spectrum and infrared.

## **2. Spread spectrum RF in the 900 Mhz or 2.4 Ghz bands**

Spread spectrum is currently the most widely used transmission technique for wireless LANs. The nature of radio signals used for data transmissions RF portable data collection systems rely on radio waves to transmit information to a remote computer or wired network interface. It was initially developed by the military to avoid jamming and eavesdropping of the signals. This is done by spreading the signal over a range of frequencies, that consist of the industrial, scientific, and medical (ISM) bands of the electromagnetic spectrum. The ISM bands include the frequency ranges at 902 MHz to 928 MHz and at 2.4 GHz to 2.484 GHz, which do not require an FCC license.

Radio signals consist of a carrier frequency to which information (audio, video, or digital data) is added in a process called modulation. Modulation creates sidebands on both sides of the carrier frequency, and it is these sidebands that carry the information to be transmitted.

Radio receivers use demodulators to get rid of the carrier frequency and extract the desired information. The person operating the receiver needs to know what frequency to tune into (the carrier frequency) before the receiver can do the demodulation. Also, the receiver must be using the correct method of demodulation that corresponds to the method used by the transmitter. This avoids interference between adjacent carrier frequencies, and maintains a degree of privacy.

### *Spread spectrum radio*

Spread spectrum transmitters maintain user privacy and avoid interference by the way they encode their frequency signals. They purposely spread their signals across a very large band of frequencies, and rely on the fact that others in that band are doing the same. Each receiver must



know what spreading pattern or code the transmitter is using in order to decode the signals being sent.

Because the FCC allows very wide bandwidths for spread spectrum radio transmissions, very high data rates are possible. Typically, the bit rates are in the range of 200 Kbps to 2Mbps. One issue associated with spread spectrum radios is receiver signal-to-noise as compared to a narrow-band transmission. Reduced signal-to-noise of a spread spectrum signal is regained by the use of a despreading process in the receiver that boosts the level of the despread signal. This is called processing gain. Range and coverage are often increased by using a network of repeaters that receive, amplify, and retransmit the signal.

The two most popular methods of encoding spread spectrum signals are called direct sequence (DS) spread, and frequency hopping (FH). As there is a good deal of question about which is best, a comparison of the two methods is presented.

#### Frequency Hopping (FH)

In FH systems, the radio transmitter hops from one carrier frequency to another at a specific hopping rate, in a specific sequence that appears to be a random pattern. Each carrier frequency and its associated sidebands must stay within the channel width defined by the FCC. If only the intended receiver knows the transmitter's hopping pattern, then only that receiver can follow the transmission. Other FH transmitters will be using different patterns, which usually will be on noninterfering frequencies. There is a communications protocol that transmitters and receivers employ to cover those instances when two different transmitters attempt to use the same frequency simultaneously. In those cases the data is retransmitted on the next hopping frequency.

The FCC allows FH systems to define their own channel spacing up to a maximum 500 kHz bandwidth in the 902 MHz band, or a 1MHz bandwidth in the 2.4GHz band. There also are FCC requirements on the amount of time the transmitter can spend on any one channel, and the number of channels that must be used. This is done to avoid "collisions" between different transmitters. The FCC dictates that the transmitters must not spend more than 0.4 seconds on any one channel every 20 seconds in the 902 MHz band and every 30 seconds in the 2.4-GHz band. Also, the transmitters must hop through at least 50 channels in the 902-MHz band and 75 channels in the 2.4-GHz band--a channel consists of a frequency width which is determined by the FCC. The IEEE 802.11 committee has drafted a standard that limits frequency hopping spread spectrum transmitter to the 2.4-GHz band.

#### Direct Sequence (DS) Spread

The other type of spread spectrum communication is called direct sequence spread spectrum, or pseudonoise. This method seems to be the one that most wireless spread-spectrum LANs use. Rather than hop around the band, DS spread radios broaden the bandwidth of their transmissions by artificially increasing the data bit rate. This is done by breaking each bit into 10 or more sub-bits called "chips". For example, if 10 chips are used, the apparent data rate and resulting bandwidth also are increased proportionally. This spreading code is what allows multiple direct sequence transmitters to operate in the same area without interference.

A spread spectrum transmitter with a unique spread code cannot create the exact same side-bands (spectral lines) as another transmitter using a different code. A receiver having the same



despreading code as the transmitter can extract information from a DS spread signal. The receiver circuit that does this is called a correlator, and it collapses the spread signal back down to just the data side bands. This is done by matching the proper spread code to the received spread signal, and thus removing the effects of chipping. The resulting signal is demodulated to extract the data.

Removing the chipping also allows the modulated signal to be filtered at a narrow bandwidth. Filtering helps reject interference from other transmitters. This rejection is known as the processing gain of the despreading correlation process.

Processing gain is a direct consequence of the direct sequence radio signal spreading and despreading process. It refers to the increase in signal-to-noise ratio that results from this process, and is required for successful data communications. Processing gain increases as the number of chips per data bit increases, and this can be manipulated by the system designer to get the desired effect.

As with frequency hopping spread spectrum, the FCC has also set rules for direct sequence transmitters. Each signal must have ten or more chips. This rule limits the practical raw data throughput of direct sequence transmitters to 2 Mbps in the 902-MHz band and 8Mbps in the 2.4-GHz band. Unfortunately, the number of chips is directly related to a signal's immunity to interference. In an area with lots of radio interference, you'll have to give up throughput to avoid interference. The IEEE 802.11 committee has drafted a standard of 11 chips for direct sequence spread spectrum.

#### *Performance Comparison*

Frequency hopped signals will generally have better adjacent channel selectivity compared to DS spread signals. But FH radios must hop through 50 channels. The FCC requires this to keep spectrum usage uniform and random. Selective use of channels is not allowed in frequency hopping. DS radio users have the freedom of selecting the channels that have the least amount of traffic and interference in their area. This usually results in better overall reliability.

It is sometimes argued that DS spreading results in a weaker signal-to-noise ratio than the narrower FH signals. The logic is that DS spreading lowers the signal power at any one frequency. However, the processing gain of the despreading correlator regains the apparent loss in power when the correlator signal is collapsed back down to the data bandwidth. In reality, DS spread signals can actually be received and correlated even when they are lower than the accompanying noise on the channel.

DS spread radios also offer the opportunity for better power management than FH radios. A DS radio can more easily rely on the wireless network access points to determine when it can shut down to conserve power. FH systems are forced to stay on more of the time because of the need to constantly synchronize their hopping sequence with that of the RF network access points. However, FH radios currently use less power than direct sequence radios and generally cost less. Therefore, battery life for an entire unit is a toss-up.

Direct sequence radios have a practical raw data rate of 8 Mbps and frequency hopping radios have a practical limit of 2 Mbps. So as high performance is key and interference will not

generally a problem, the favor goes to DS. With either method of spread spectrum the end result is a system that is extremely difficult to detect, does not interfere with other services, and still carries a large bandwidth of data.

### 3. Infra-red

Infrared LANs use infrared signals to transmit data. This is the same technology used in products like remote controls for televisions and VCRs. These LANs can be setup using either a point-to-point configuration or a sun-and-moon configuration where the signals are diffused by reflecting them off of some type of surface.

The major advantage of infrared is its ability to carry a high bandwidth, but its major disadvantage is that they can easily be obstructed, since light cannot pass through solid objects.

The group pushing infra-red technology standards is the Infrared Data Association (IrDA), whose stated purpose is "to create an interoperable, low cost, low power, half-duplex serial data interconnection standard that supports a walk-up, point-to-point user model that is adaptable to a wide range of appliances and devices." IrDA will soon represent lower costs than current wire/cable/connector setups thus becoming ubiquitous. If it works over a wire/cable it will work over the IrDA infrared data link. These visions led to the IrDA Standard herein summarized with three mandatory compliance level sections of the Physical, IrLAP & IrLMP (plus optional sections including the Higher Speed Extensions (1.15 & 4 Mbits/sec), IrCOMM, TinyTP & PnP) and titled the IrDA Serial Infrared Data Link Standard, Version 1.1. IrDA Serial Infrared Physical Layer Link (IrDA-SIR). Key Features of IrDA-SIR/Serial IR Physical Layer are listed as follows.

Low Cost Implementation: The standard was developed to utilize low cost components with implementation costs to the manufacturer expected to be only several dollars per device. With expected integrated chips including IrDA functionality there will be only the very low cost (less than a dollar) of common opto-electronic components. No special or proprietary hardware is required.

Low Power Requirements: IrDA-SIR is designed to be power efficient so that it will not be a drain on the batteries of portable devices like notebook computers, PDAs, mobile phones and other handheld IrDA devices. It has an advantage over diffuse IR since it uses very low power when transmitting.

Directed, Point-to-Point Connectivity: IrDA-SIR is designed to be easy to use and supports a conscious connectivity usage model. Directionality of the IR beam provides additional user comfort of not unintentionally "spilling" the transmitted data to nearby devices. However, the angular spread of the IR beam does not require the user to align the handheld device perfectly at the target device to achieve an IR link (usu. within 10-15°).

High Noise Immunity: IrDA-SIR is specified to achieve bit error rates of better than 1 in  $10^9$  at ranges of up to 1 meter, while still providing a high level of noise immunity within a typical office environment illuminated with fluorescent light (suggested that this not be directly overhead) as well as in the sunlight. Appropriately implemented, a product would also conform to level 3 severity electromagnetic fields as defined in IEC 801-3 specifications.

Optimized for Data Transfers: IrDA-SIR is a half-duplex system with the maximum UART based data rate of 115.2 kbits per second. Because the design can be driven by a standard UART, its data rate can be easily programmed from software to a lower data rate to match with slower devices. Also note that version 2.0 also defines non-UART environments (see High Speed Extensions - 1.15 & 4.0 Mbit/sec options.)

Other Features: The IR LED peak wavelength is specified to range from 0.85-0.90  $\mu\text{m}$ .

The IrDA-SIR physical hardware is very simple. It consists of an encoder/decoder (which performs the IR transmit encoder and IR receiver decoder) and the IR transducer (which consists of the output driver and IR emitter for transmitting and the receiver/detector). The encoder/decoder interfaces to the UART, which is expected to already be present in most computers.

The IrDA-SIR specification takes a standard asynchronous serial character stream from the UART (where a frame is defined as a start bit, 8 data bits, no parity bit and a stop bit) and encodes the output such that "0" is represented by a pulse and "1" is represented by no pulse. A pulse is further defined as occupying a nominal minimum of 1.6 microseconds to a maximum of 3/16th of a bit period, the length of which is inversely proportional to the bit rate of the data (ie, the slower the data rate, the longer will be the pulse). This pulse stream forms the input to the driver for the IR emitter that converts the electrical pulses to IR energy.

The IrDA-SIR specifications were established for worst case optical link parameters needed to support the defined link performance. Optical interface specifications are independent of technology and apply over the life of the link and are readily testable for conformance.

#### IrDA Infrared Link Access Protocol (IrLAP):

The Infrared Data Association has defined and adopted a link protocol for the serial infrared link. IrDA's Infrared Link Access Protocol, or IrLAP, is derived from an existing asynchronous data communications standard (an adaptation of HDLC.) A key element of IrLAP is the relationship between a primary and one or more secondary stations.

Primary and Secondary Station Roles: The data transfer operation of the data link protocol has remained very close to its original heritage from HDLC. A data link involves at least two participating stations. IRLAP provides two roles for participating stations: (1) Primary (commanding) station and (2) Secondary (responding) station. The primary station has responsibility for the data link. All transmissions over a data link go to, or from, the primary station. IRLAP communication links can be point-to-point or point-to-multipoint. There is always one and only one primary station; all other stations must be secondary stations. Any station that is capable can contend to play the primary station role. The role of primary is determined dynamically when the link connection is established and continues until the connection is closed (the exception is that there is a method provided for a primary and secondary on a point to point link to exchange roles without closing the connection).

#### Framing Procedures and Data Link Operation:

IrLAP uses most of the standard types of frame defined by the HDLC standards. The frames are classified by function as follows: unnumbered or U frames, supervisory or S frames and information or I frames. U frames are used for such functions as establishing and removing connections and discovery of other station device addresses etc. I frames are used to transfer information from one station to another. S frames are used to assist in the transfer of information, they may be used to specifically acknowledge receipt of I frames (I frames can implicitly acknowledge other I frames also) and to convey ready and busy conditions.

#### IrDA High Speed Extensions (1.15 & 4.0 Mbit/sec data speed options):

IrDA has included 1.152 & 4.0 Mbit/sec operational modes which need a few important upgrades and modifications to the transceiver circuitry and driver software needed for these higher speeds. The main architectural difference is related to the need for the Communications Controller. Note all implementations are backward compatible to the IrDA compliancy mandate of 9600 b/s negotiation (and likely speeds up to the UART based 115 kb/s.)

The 1.152 Mb/s mode requires a new circuit or component, termed a Communications Controller, since this mode does not directly interface to a standard UART as does the 115 kbps mode as described in version 1.0. The Communications Controller provides monitoring and data flow control between ISA Bus/FIFO and the UART/FIFO and allows direct access by the external bus.

The 4.0 Mbps mode uses Pulse Position Modulation (PPM) data encoding with four possible chip or time slice positions per data symbol. The system can recognize and prevent interference with UART based systems by including the emission of a SIR Interaction Pulse (SIP) at least every 500 milliseconds. High speed modes are transparent to IrLAP and IrLMP with speed options negotiated during normal IrLMP discovery processes.

#### Comparison SS and IR:

	Spread Spectrum	Infrared
Frequency	902-928 MHz ; 2.4-2.4385 GHz; 5.725-5.825 GHz	$3 \times 10^{14}$ Hz
Maximum coverage	100-800 ft., or up to 50,000 ft <sup>2</sup>	40-130 ft., or up to 5000 ft <sup>2</sup>
Line of sight required?	No	Yes
Transmit power	< 1 W	25 mW
License required?	No	No
Max. Rated speed	2-8 Mbps	1-4 Mbps

#### What products are available:

Company	Product	Radio/IP	Frequency	AdvertizedSp eed	AdvertizedDi stance
---------	---------	----------	-----------	---------------------	------------------------

AT&T	WaveLAN	Radio	902-928 MHz	2 Mbps	800 ft.
Digital	RoamAbout	Radio	902-928 MHz	2 Mbps	800 ft.
IBM	Infrared	IR		1Mbps	17 ft. x 17 ft.
	Wireless				
	LAN Adapter				
InfraLAN	InfraLAN	IR		10 Mbps	90 ft.
Technologies					
Photonics	Wide Area	IR		1 Mbps	20 ft. x 20 ft.
	and Point-to-				
	point products				
Solectek	AirLAN	Radio	902-928 MHz	2 Mbps	800 ft.
Windata, Inc.	FreePort	Radio	2.4 GHz and	5.7 Mbps	260 ft.
			5.8 GHz		
RadioLAN	RadioLAN/10	Radio	5.8 GHz	10 Mbps	office: 150 ft. open: 300 ft.

### AirLAN

AirLAN by Solectek is based on radio technology originally developed by NCR Corp. Except for its parallel-port Wireless LAN adapter, Solectek's technology is based on OEM products from AT&T and Digital.

### RadioLAN

The Radio LAN/10 family of 10-Mbps access units for wireless 10BaseT Ethernet LANs include an ISA Bus version and a PCMCIA version (available in late 1996) for stand-alone networks. RadioLAN combines adapter, radio transceiver and base station into a single, compact unit. Each Radio LAN/10 access unit is available in two versions a wireless adapter and a wireless plus Ethernet adapter (an access point). Both versions support relay, a method for connecting outlying nodes into the wireless network.

RadioLAN/10 matches the full 10-Mbps data rate of Ethernet LANs. RadioLAN products are compatible with IEEE 802.3 standards and require no FCC licensing. In addition, they can interoperate unmodified with standard 10BaseT wired networks. This technology takes advantage of the 5.8-GHz radio frequency(RF) band, which offers wider bandwidth than the 902-928-MHz or 2.4Ghz. It utilizes a focused narrow-band technique, originally developed for satellite systems, to achieve high speed at a per-node cost equivalent to a 10BaseT solution consisting of an adapter card, hub port and cabling. The system uses just one percent of the power required for cellular phones.

### RoamAbout

The RoamAbout PCMCIA Network Adapter is a PC Network Interface Card (NIC) for wireless LANs. The Network Adapter operates in a PC with a Type II PCMCIA slot that conforms to the PCMCIA release V2.01 specification. An antenna is externally connected via an 18" (0.5 meter) cable. The RoamAbout PCMCIA Network Adapter communicates with the RoamAbout

PCMCIA Network Adapter in other portable computers, the WaveLAN NIC in stationary computers, or the RoamAbout Access Point for connectivity to the wired network.

### WaveLAN

A premier spread-spectrum network system manufactured by NCR Corporation. This is a 2Mbps network system that utilizes a proprietary protocol. WaveLAN also uses a robust error-checking protocol that can detect and correct most transmission errors, and a data-encryption option that makes the network highly resistant to electronic eavesdropping.

Current bandwidths

Work of UCLA group

4. Digital cabling (e.g., Ethernet connection) through a PCMCIA card attached to the hand-held scanner.

Pros and cons of each

II. Connection from the portable/mobile base station to the remote physician:

A. Could be one of the following:

1. A non-line-of-sight high-frequency RF connection (2.4 Ghz) to a base-station concentrator (RAP) on the battlefield that would then beam the data up to a satellite (possibly Ka-band) or aircraft
2. Directly transmit from the portable/mobile base station to the satellite using a MMIC antenna attached to the vehicle (FAST HMMV or armored personnel carrier) or a portable antenna.

*Research, analysis and specification of telecommunications connectivity on the battlefield (MIL COM) for the portable ultrasound system: codec to codec and ultrasound system to codec.*

### Battlefield Information Transmission System

Figure 1 is a high-level concept drawing of the digital battlefield communications infrastructure that will be developed and deployed in phases over the next decade. It consists of several land, air and space-based systems for the transmission of voice, text, data, graphics, images and video. The entire concept is known as the Battlefield Information Transmission System (BITS).

The Battlefield Information Transmission System (BITS) is a direct outgrowth of the Army Digitization Master Plan (ADMP). The ADMP describes the process that will lead to seamless interoperability across the battlefield, the capability required to transform the Army into a 21st-century force (Force XXI), and provides guidance for developing, testing, and producing digital hardware and software to meet Force XXI requirements. BITS is the umbrella program under which the elements needed to support Force XXI information-transport requirements come together.

Three documents provide the concepts and requirements for battlefield digitization: (1) the Horizontal Interoperability Battle Command Mission Needs Statement, (2) the Army Battle Command System Common Operating Environment/Common Applications Operational Requirements Document, and (3) the Force XXI Battle Command for Brigade and Below Operational Requirements Document. To achieve the capabilities defined in these documents, the Army Digitization Campaign Plan was developed. The four main thrusts of the Army Digitization Campaign Plan are:

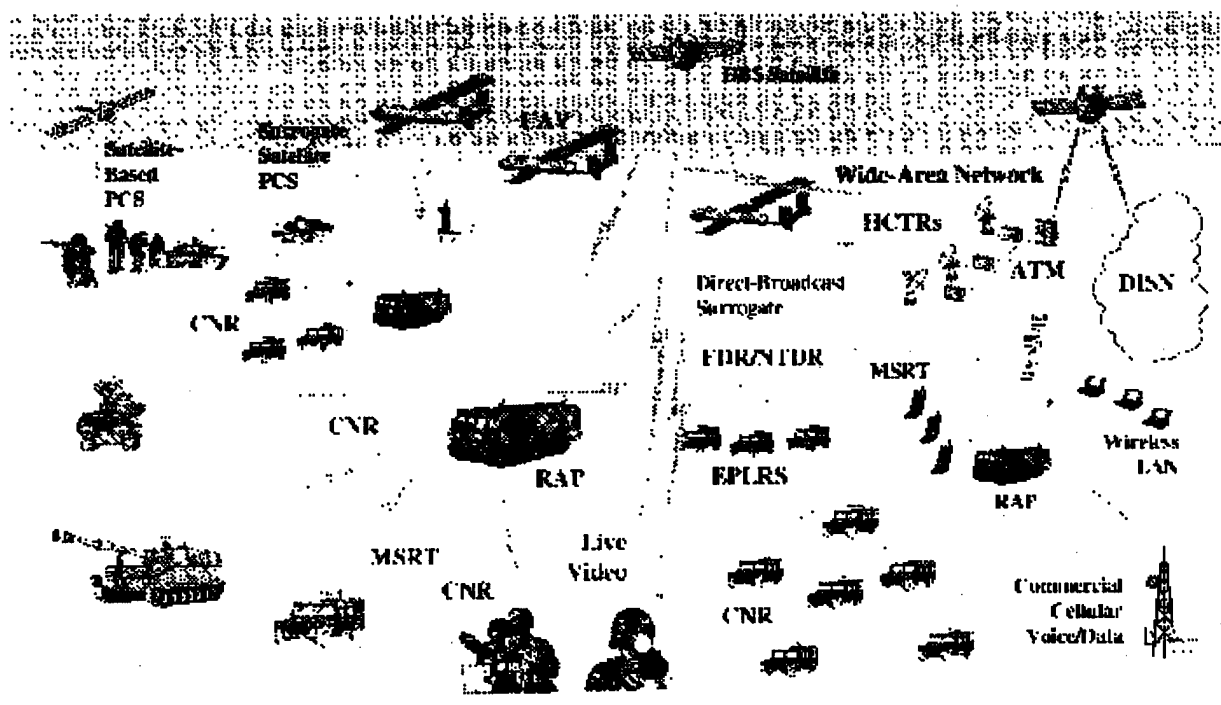


Figure 1. Digital Battlefield Communications Architecture Elements.

(1) Acquire a digitized capability for lower echelon forces, (2) Develop a tactical Internet (TI) capability, (3) Integrate all battlefield operating systems, and (4) Manage the evolution of BITS.

BITS is seen as a next-generation requirement because the future digital load is expected to exceed the combined capacity of the legacy systems (e.g., Single Channel Ground and Airborne Radio System [SINCGARS], Enhanced Position Location Reporting System [EPLRS], and Mobile Subscriber Equipment [MSE] Tactical Packet Network [TPN]). These three systems, interconnected with Internet Protocol (IP)-compliant routers, comprise the Tactical Internet (TI - Figure 2). Distribution of digital information among the profusion of devices such as command and control (C2) systems, sensor platforms, and embedded computers will become the dominant activity for information transport. Requirements for imagery and real-time video in addition to voice and data point to the need for multimedia services.

### Advanced Warfighting Experiments

Advanced Warfighting Experiments (AWEs) are major events conducted in a tactically rigorous environment to confirm experimental hypotheses regarding increases in warfighting capability. AWEs are intended to demonstrate improvements in force-effectiveness as a result of fielding digital information technologies, and by changing organizational designs and tactics, techniques, functions, and procedures. Equipment will be examined in these experiments to establish an early understanding of their warfighting potential. Each experiment will build on the results of previous experiments, creating the "rolling baseline" assessment to measure force-effectiveness increases.



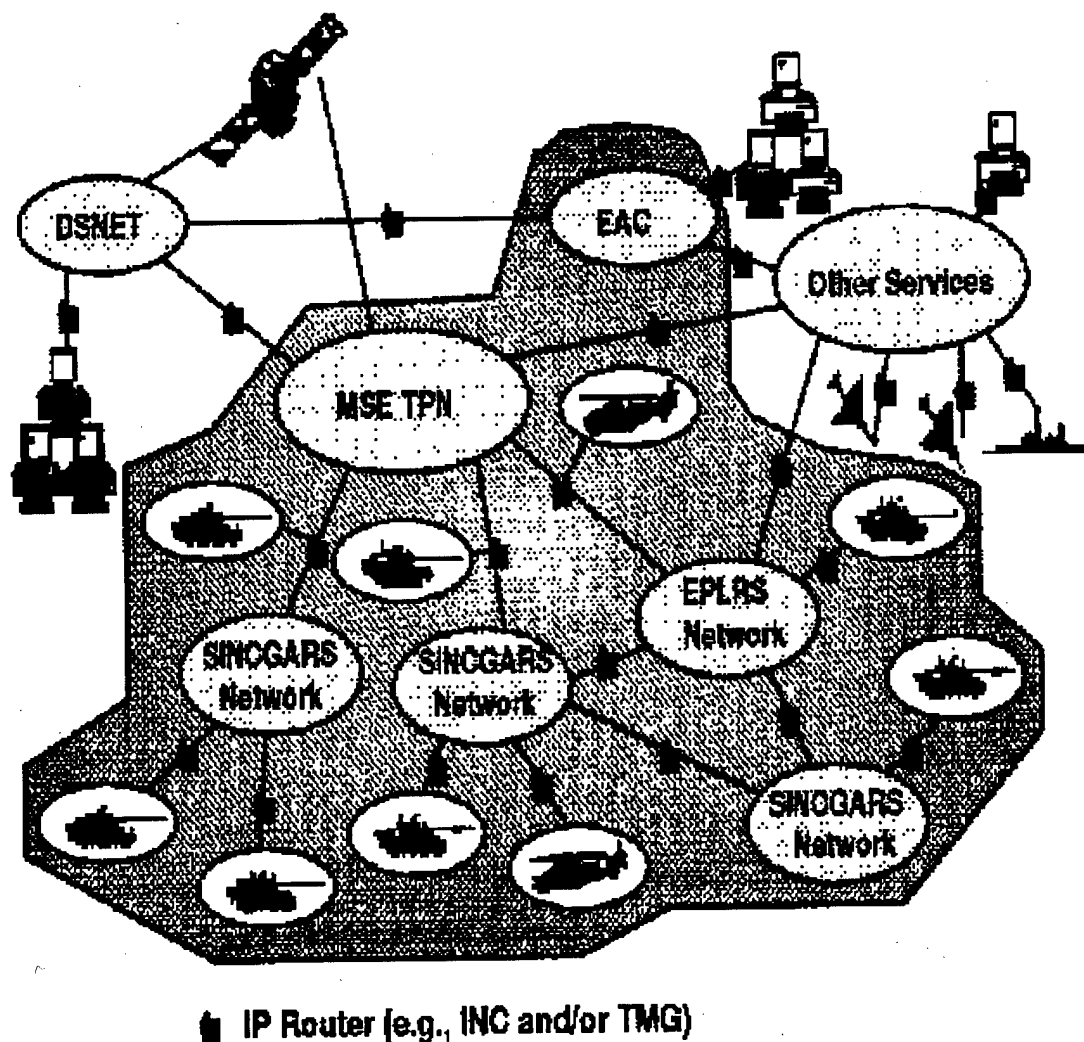


Figure 2. Tactical Internet.

Key AWEs in the near future are:

- Warrior Focus (November 1995)
- Task Force (Brigade) XXI (February 1997)
- Division XXI (February 1998)
- Corps XXI (February 1999).

The migration from today's legacy communications systems to the objective BITS will be an evolutionary process. BITS elements will be fielded as part of an incremental buildup beginning with Task Force XXI (TF XXI) and continuing into the post-Year 2000 time frame. The TF (Brigade) XXI, Division XXI, and Corps XXI AWEs will demonstrate the incremental buildup of BITS capabilities in simulated warfighting experiments. The BITS evolution is shown in Figure 3.

As the current schedule for the Cozumel prototype is February 1998, it will most likely not be possible to participate in the Division XXI AWE, but a real possibility for Corps XXI. The authors have been and will continue to be in contact with personnel at Fort Gordon, GA and Fort Monmouth, NJ to arrange for participation of the Cozumel prototype in these and other evaluation exercises.

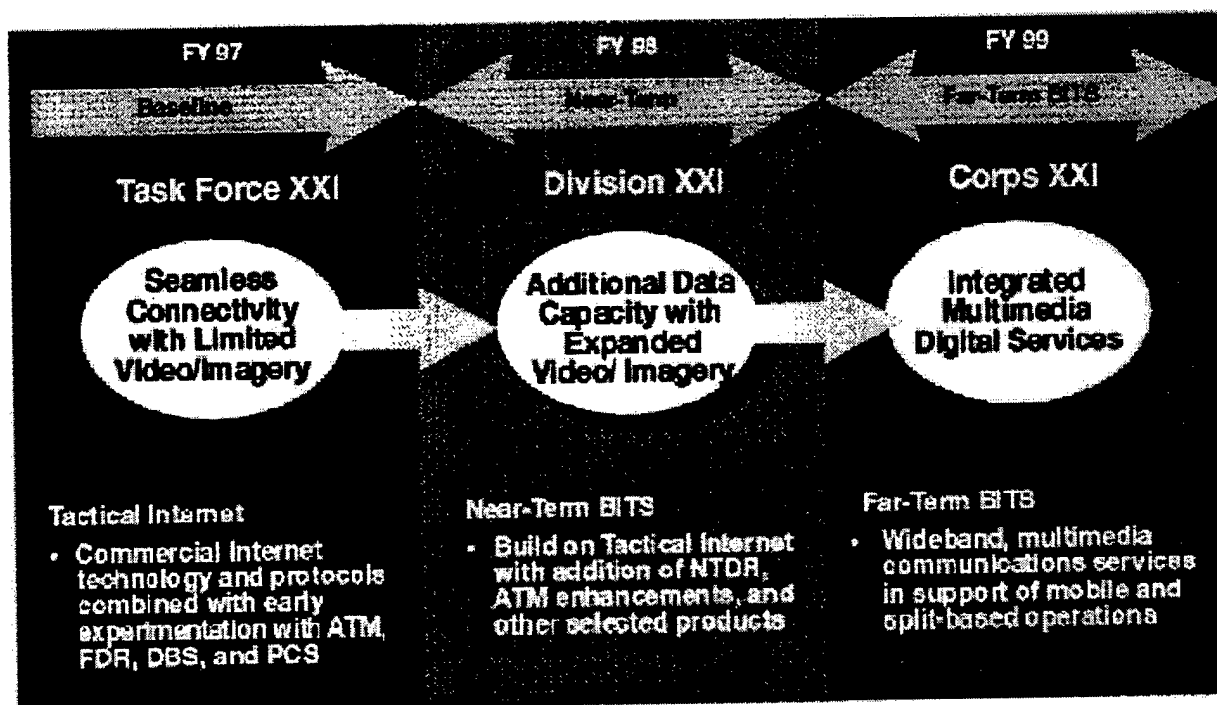


Figure 3. BITS evolution.

#### Current Infrastructure

The current battlefield communications infrastructure consists of the following three legacy systems: (1) Single Channel Ground and Airborne Radio System (SINCGARS), (2) Enhanced Location Reporting System (EPLRS), and (3) Mobile Subscriber Equipment (MSE) Tactical Packet Network (TPN). The MSE/TPN consists of heavy trucks and HMMVs with 30-40 ft masts. There are typically 30 of these MSE nodes per division and these remain static while transmitting. These units are much like commercial TV reporting vans with erectable microwave masts. As microwaves are used, it is necessary to have a direct line of sight. The MSE nodes are deployed about 10-20 kilometers apart and provide a T-1 (1.544 Mbps) -like bandwidth backbone for battlefield telecommunications. The 1.5 Mbps is shared between many users using Time Division Multiplexing (TDM). The maximum bandwidth one single channel can use is 16 kbps, however, multiple lines can be used through the employment of an inverse multiplexer. This network is used mostly for voice service connection packet switching.

## ATM Technology Integration

The objective of the ATM (Asynchronous Transfer Mode) technology integration program is to support the insertion of ATM technology into the Army's tactical wide-area communications system through a series of planned product improvements (ultimately replacing MSE with the next-generation switching system). The first phase provided incremental improvements to the current MSE system. ATM experiments conducted during Unified Endeavor in April 1995 (see Figure 4) served as the baseline for this program. During Unified Endeavor, seven ATM switches were installed in MSE shelters, enabling MSE voice traffic to be combined with additional data traffic over the existing MSE backbone network. The additional data traffic was used to support collaborative planning and desktop video conferencing at four deployed sites. Sun workstations using Paradise video teleconferencing boards and Internet Protocol - IP-based transmission were used.

Despite the success demonstrated during Unified Endeavor, the bandwidth between MSE nodes were still limited to between 512 and 1544 kbps, which severely hampers the advanced bandwidth and switching capabilities of the ATM switches. The second phase would introduce high-bandwidth radios (HCTR) with OC-1/3 (45/155 Mbps) bandwidth between major communications nodes on the battlefield (see Radio Access Point below).

## BITS Strategic Framework

The approach used in developing, demonstrating, and fielding BITS capabilities consists of the three phases shown in Figure 5. The R&D phase is the responsibility of CECOM (Communications-Electronics Command) and other R&D activities and culminates in technology insertion into an AWE or other field exercise. The leave-behind phase consists of providing additional equipment to operational units, for a period of up to two years, for the purpose of product evaluation and requirements definition. During the acquisition phase, the products developed and refined during the first two phases are handed off to the PEO (Program Executive Office)/PM (Project Manager) for acquisition and fielding.

## Far Term BITS Strategy

The Tactical Internet (Figure 2) is the TF XXI baseline from which BITS will evolve. Asynchronous transfer mode (ATM) switching combined with the Area Common User System (ACUS) of MSEs will provide video teleconferencing capabilities. High-capacity trunk radios (HCTR - Figure 6) will be used will replace ACUS LOS (line-of-sight) radios for terrestrial-based transmission at 45/155 Mbps. Direct-broadcast satellite (DBS) will provide a means of disseminating wideband imagery independent of terrestrial infrastructure and topography. Commercial terrestrial PCS (personal communication systems) as an upgrade to the MSE will be used for most low-bandwidth voice and data transmission applications.

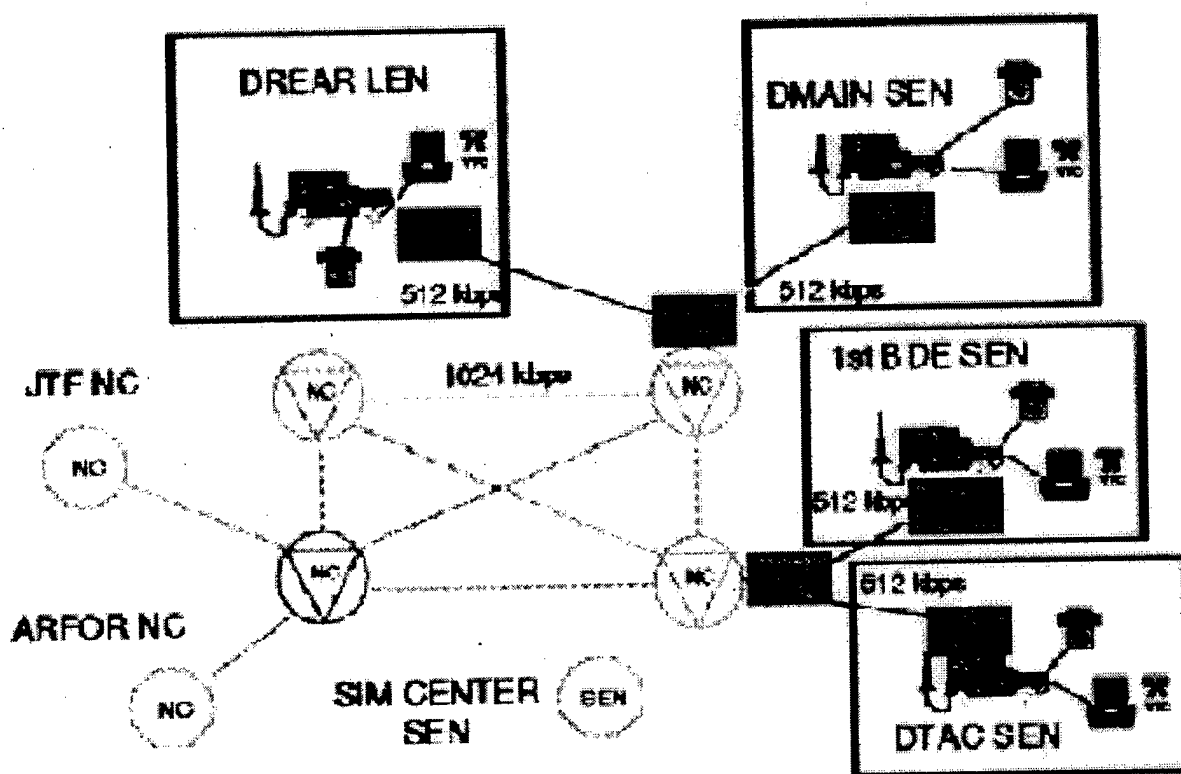


Figure 4. Unified Endeavor Multipoint Video Teleconferencing Experiment

### Radio Access Point

Radio access points (RAPs - Figure 7) will extend wideband trunks from tactical point-to-point backbone to lower echelons (brigade and below), initially providing high bandwidth bridges between MSE networks (upgrades to 10 Mbps between nodes) and eventually replacing them. They will support narrowband integrated voice, data, and video access to/from users located on highly mobile platforms as well as the individual soldier communications. The RAP relies on four key components: (1) ATM switching, (2) HCTR, (3) airborne relay (UAV - unmanned aerial vehicle, or satellite), and (4) "on-the-move" (OTM) phased array antenna. Initially the data rate

of the RAP will be T-1 (stationary) and eventually 45/155 Mbps. In a mobile state, the RAP will initially provide 2.4 to 56 kbps bandwidth. Field demonstration is slated for the Corps XXI AWE, so it may be possible to tie Cozumel into a RAP during that exercise.

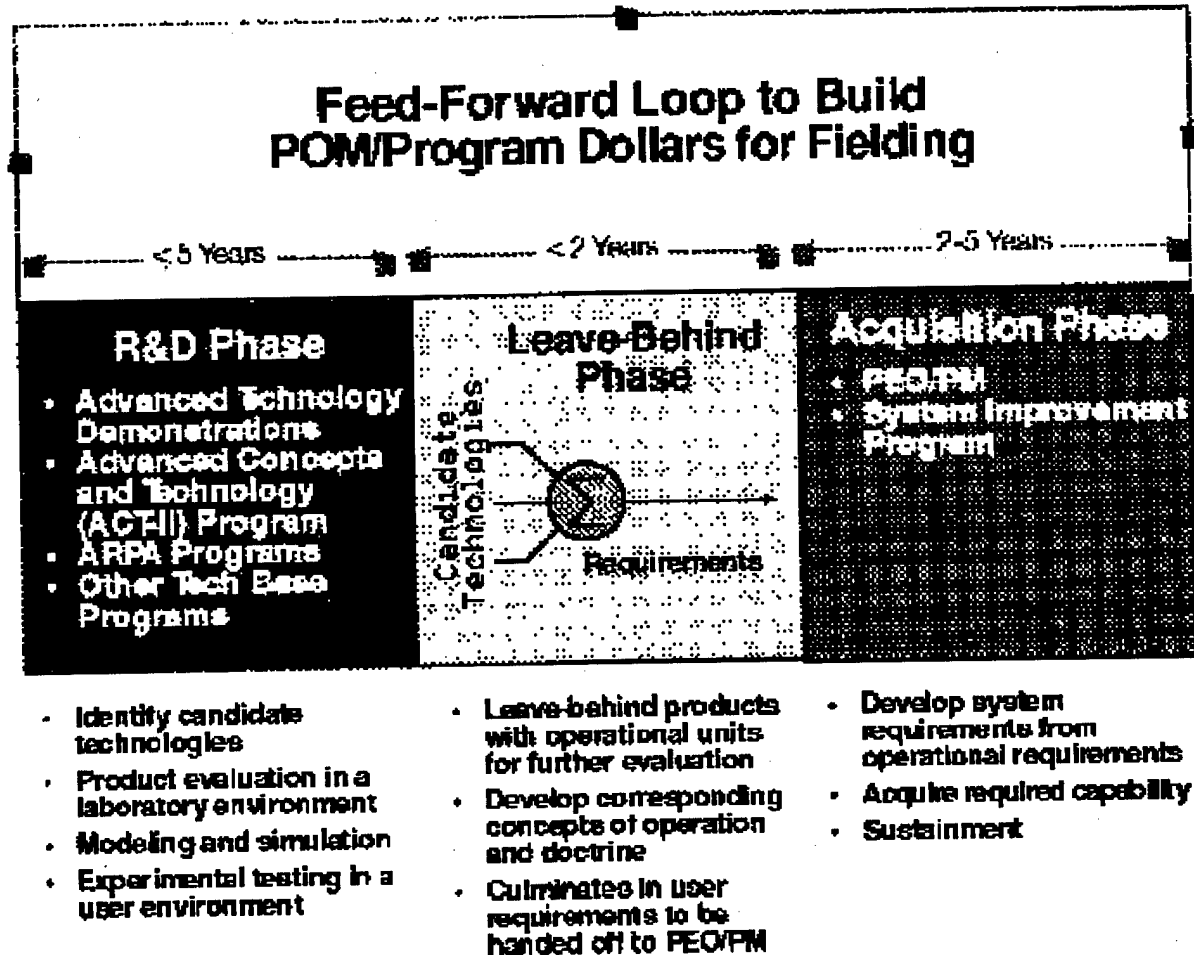


Figure 5. BITS strategic framework.

### Direct Broadcast Satellite

The Direct Broadcast Satellite (DBS - Figure 8) program, in coordination with the Joint Global Broadcasting System (GBS), will develop an Army DBS system providing the flexibility required to support operations while maximizing the benefit of low-cost commercial developments. Three commercial DBS terminals will be acquired, modified to work with standard Ku-band antennas, and integrated with Sun workstations. They will be used for AWEs beginning with TF XXI. An uplink capability will be provided for use during TF XXI which will use a standard Ku band transmitter/antenna. This will provide an end-to-end capability for the TF XXI AWE and subsequent demonstrations.

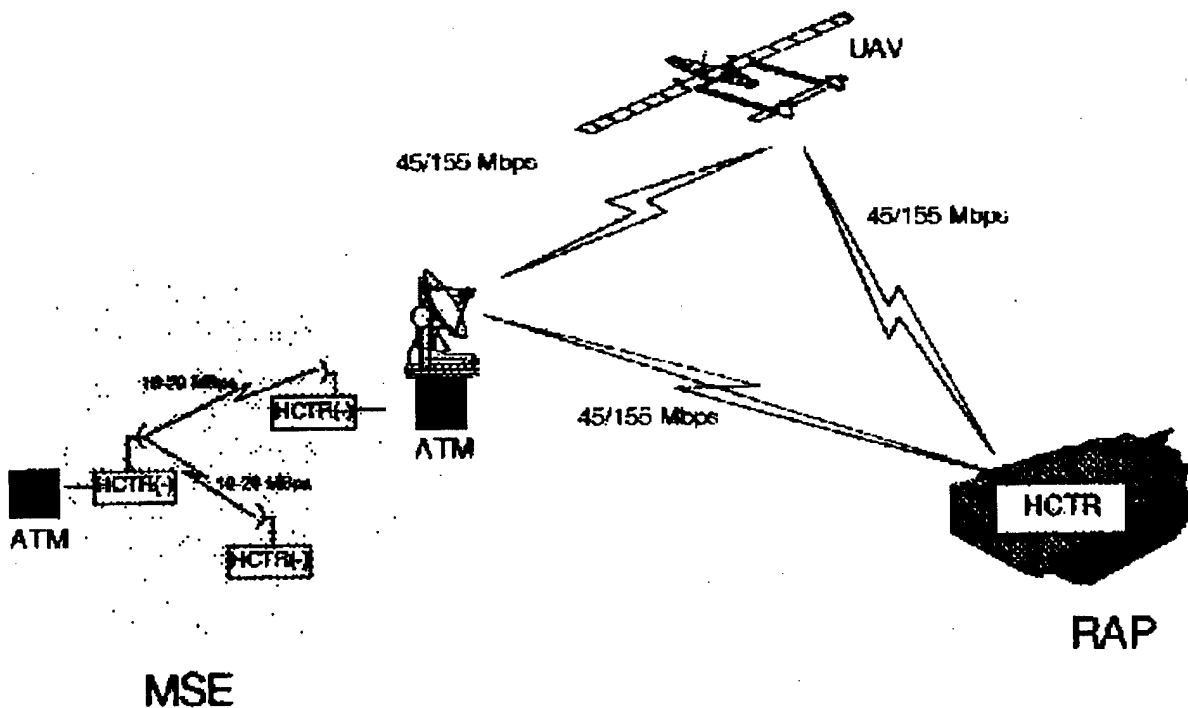


Figure 6. High-Capacity Trunk Radio

A DBS programming center will be developed/acquired to consolidate, schedule, and control data/video dissemination. This will be used to support the Corps XXI AWE. Also, an airborne DBS transponder will be developed to provide and demonstrate a global capability for in-theater data dissemination under direct control of the theater commander. While the ideal platform is the UAV (production 2002), the goal is to develop a system that is platform-independent. An effort to develop a system to receive DBS data on a moving platform will focus on antenna subsystems development. Current plans are to develop and produce a single unit for demonstration at the Corps XXI AWE.

#### Terrestrial PCS

The objective of the Terrestrial PCS program is to investigate the feasibility and benefits of using emerging commercial cellular/PCS technology as an enhancement to the Army's MSE (Figure 9). This system currently provides intermixed digital

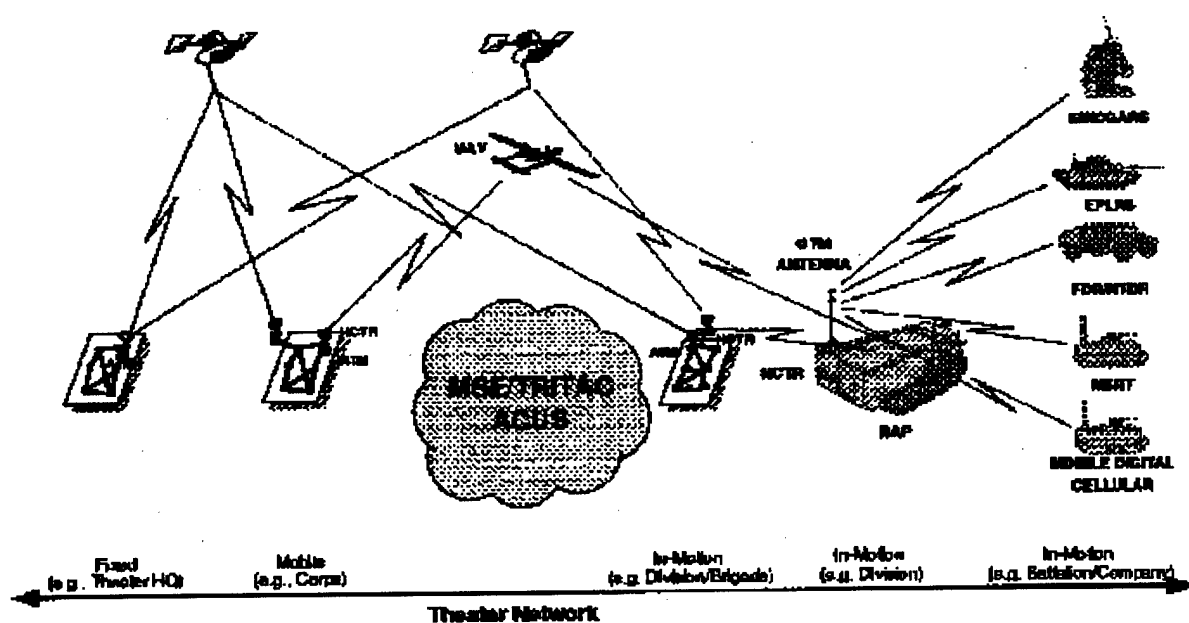


Figure 7. Radio access point (RAP).

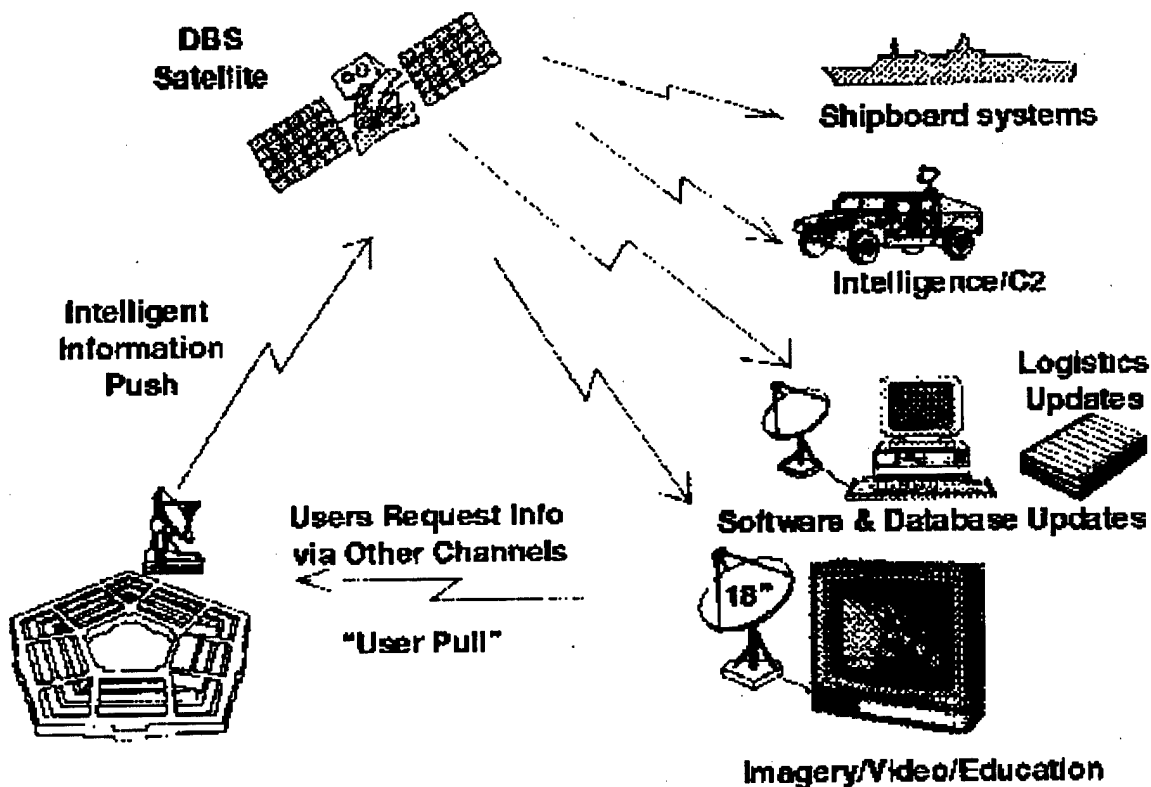


Figure 8. Direct broadcast satellite (DBS).

voice and data transmission over multiple 9,600-baud half-duplex channels. Handheld Personal Digital Assistants and generic laptop 486 computers are interconnected via this system. Global Positioning System (GPS) receivers and heads-up displays are also integrated with the computing devices. The hardware, software, and a gateway to the Battalion and Below Command and Control (B2C2) system was tested during the Warrior Focus AWE. This hardware will serve as the baseline hardware for use during the TF XXI AWE. The hardware includes one 12-channel base station and approximately 50 handheld radios.

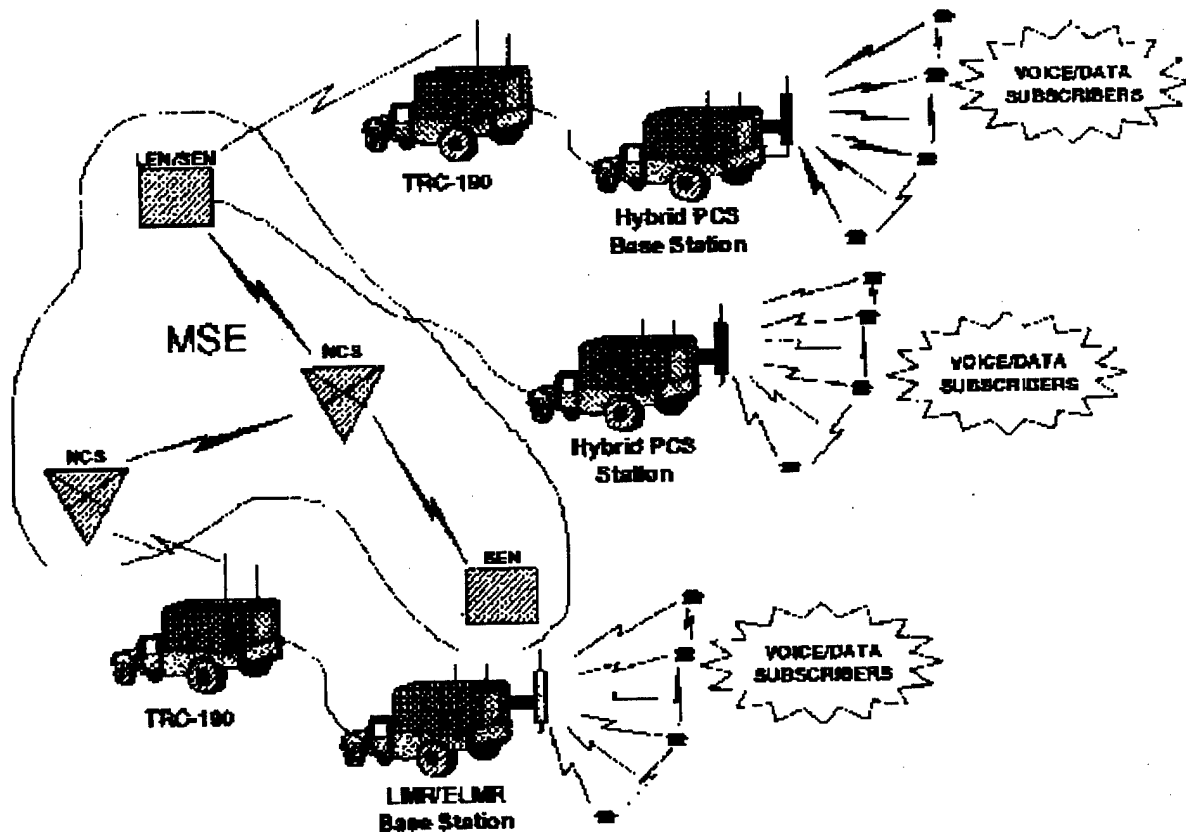


Figure 9. Terrestrial PCS (Personal Communications System).

#### Battlefield Communications Take-Aways

Current communications linkages on the battlefield would consist of 16 kbps channels at the 2nd echelon (brigade and division support areas). These could be multiplexed together. MASH units during Operation Desert Storm and currently in Bosnia use INMARSAT satellite linkages of 56/64 kbps.

The Local Area Communications Integration Laboratory (part of the Digital Integration Laboratory, Communications-Electronics Command, Research and Development and Engineering Center at Fort Monmouth, NJ) has successfully demonstrated compressed video teleconferencing (which could be used to the handheld output video signal) using the current



MSE infrastructure with ATM switches at each of the MSE nodes during Unified Endeavor in April 1995.

Increasing the available bandwidth for the BITS infrastructure will be an ongoing project for the next decade. Portions of BITS will be demonstrated during several Force XXI exercises, one of which (Corps XXI - February 1999) the hand-held unit could be demonstrated. It is anticipated that it will take 3-6 years for general deployment of the BITS infrastructure. As generic Internet Protocol will be used throughout BITS, transmission of still images and video clips should not be a problem, the limitation being the available bandwidth which could be as low as current digital modems (28.8-33.6 kbps) and as high as 10 Mbps, depending on where on the battlefield the ultrasound unit is used.

#### Connection From The Portable/Mobile Base Station To The Remote Physician

Either IR or RF will be used from the handheld unit to a base-station connected to an IP network in a MASH/EVAC setting. Spread-spectrum RF is preferable due to the limitation of line-of-sight and small angle of acceptance. A non-line-of-sight high-frequency RF connection (e.g., 2.4 GHz) from the handheld unit to a base-station (FAST) is preferable on the battlefield. As regards bandwidths, even with full implementation of BITS, medical imagery will most likely have least importance and thus low bandwidth access. Thus, it would appear it will only be possible to (1) Transmit single-frames at the 2nd Echelon - Brigade level, (2) Support store and forward pertinent slices for 3D volume data set (rendering on far end) or video clips at the 2nd Echelon - Division level, and (3) possible to support interactive 2-way video from the 3rd Echelon - Corps level upwards.

#### Task 6 - Clinical Evaluation: Controlled Conditions

*Assessment of normal patients and preliminary evaluation of trauma patients for abdominal fluid using ultrasound.*

##### Executive Summary

A single prototype DARPA sponsored hand held probe ( HHU C60) was received by the University of Washington on October 29, 1998. The prototype system consists of four components: (1) a C60 curvilinear transducer with the major imaging components in it, (2) a display box with a 5 " display and components for communicating with the transducer system and a laptop computer, (3) a power supply for the display box, and (4) a laptop computer with software for controlling the imaging parameters. Unfortunately, this early prototype packaging is not suitable for use in the emergency room so no studies could be conducted in that environment. The imaging ability and overall performance of the unit was assessed in 10 volunteer subjects (9 normal and 1 peritoneal dialysis patient) by 4 radiologists and 2 expert lead sonographers. Comparisons were made with it to an ATL HDI 3000 a high level unit and ATL UltraMark 4, a midrange imaging unit. The HHU C60 was also linked via an internet telemedicine link and imaging with it was investigated and compared with the UltraMark 4. A clinical subjective likert scale (5-good, 4-moderate, 3-fair, 2-poor, and 1-unacceptable) was used to rate performance in a 7 imaging categories as well as a rating of 7 features regarding the 5" LCD display, and finally

the transducer size, ease of use, and examination time with the units were also scored. A total of 70 evaluations were performed. Finally, a brief video recording showing some results and a discussion by Dr. Carter is submitted with this report.

### **Imaging Evaluation**

**Results:** The average of all 7 categories for the three units for *overall imaging* was: HHU C60 - 4.65, UM 4 - 4.76, and the HDI 3000 - 5.0. The average of all the LCD display categories was 4.2 with the *contrast* rated the lowest at 3.97. The *transducer size* was given a 3.64 and the *ease of use* was low at 3.54 but this was mostly due to the current software for controlling the unit not being user friendly. Finally, the *examination time* was rated at 4.26 for the HHU C60 whereas it was 4.92 with the UM 4, and 5 with the HDI 3000.

**Discussion:** All US units tested were noted to do well for the detection of abdominal fluid. The HHU C60 easily detected fluid in all 4 abdominal quadrants including pelvis and gutters. An absent kidney was identified in one "normal" subject and Renal Cysts, and Calculi in another. Hydronephrosis was easier to rule out than dilated biliary ducts, respiratory motion was easily detected, and comparative echogenicity of liver versus kidney tended to be the most subtle differentiation. All examiners were surprised and pleased with the quality of the images of the HHU C60, they felt they were very acceptable for diagnostic purposes, they didn't mind the size of the probe, more rib shadowing occurred with it than the smaller probe on the UM 4 but that did not interfere with diagnosis. The only complaint was the cumbersome of the human interface for controlling the imaging parameters. Clearly that needs improvement but we realize this was an interim step in the development. All the radiologists were quite excited about the concept of such a small unit and felt it really would be useful in ambulatory situations.

### **Telemedicine Evaluation**

**Results and Discussion:** There was a slight degradation in the transmitted images, overall assessment was: HHU C60 direct - 4.65, HHU C60 telemedicine - 4.40 ; UM 4 direct - 4.76, UM 4 telemedicine - 4.59. This small degradation did not interfere with diagnosis. The value of the feedback an examiner at the patient's side gets from the remote expert by telemedicine was interestingly rated quite different depending on whether the patient examiner was a novice or already an moderate to expert ultrasound examiner. The value of the remote expert being able to see the location of the probe on the patient via video images was rated at 4.8 for the novice and 2.63 for the expert. The person who was already an expert could be guided by voice commands alone to conduct the study. Further, the value of the graphic overlay was rated at 4.2 for the novice and 3.69 for the more expert examiner. Finally, the audio channel was rated at 5 by either experienced examiners and felt absolutely necessary for this study. In comparing compression and decompression methodology for transmitting the images to the remote location higher resolution in the images was preferred over faster frame rate of the images. Overall, the telemedicine linkage, display resolution, and frame rate was felt very valuable for diagnosis when the examiner at the patient was not a radiologist.

Clinical Subjective Preference Testing  
DARPA – UW Radiology

Right Upper Quadrant

Please rate clinical image quality using the 1-5 scale (5 = best, 1 = worst)

1. Visualization of kidney/ liver contour:

Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

2. Fluid visualization: (i.e. R/O significant fluid/blood in Morison's pouch)

Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

3. Normal Respiratory Motion:

Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

4. Comparative echogenicity: (i.e. liver>kidney)

Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

5. R/O hydronephrosis:

Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

6. R/O significantly dilated biliary ducts:

Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

7. Gall Bladder visualization:

Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

US Equipment: HHU Prototype\_\_\_\_\_

Other:\_\_\_\_\_

*SUMMARY*

## **Testing and Comparison of DARPA HHU C60 Prototype**

HDI 3000	ATL UM4	HHU C60
5.00	4.76*	4.65*
----	4.59**	4.40**

\*Overall Average RUQ

\*\* Overall Average RUQ w/ Telmed/Compression

### **General Clinical Comments & Observations**

- Likert Analysis Focused on the RUQ.
- All US Units tested were noted to do well for detection of Abdominal Fluid (hemoperitoneum) including remotely controlled telemedicine.

- Fluid easily detected in all four Abdominal Quadrants including pelvis and gutters (Dialysis Subject).
- HHU C60 identified an Absent Kidney in one 'normal' subject and Renal Cysts and Calculi in another.
- Some General Observations Noted:
  - 1) Hydronephrosis easier to rule out than Dilated Biliary Ducts.
  - 2) Respiratory motion easiest to detect.
  - 3) Comparative Echogenicity of Liver vs Kidney tended to be most subtle differentiation.

## **TELEMEDICINE**

- Some Degrading of Image with compression and Decreased Frame Rate – Remains Moderate to Good in all Units Tested.
- Less Skilled Examiner greater Reliance/Preference of Image of Scanhead/Patient and of Graphic Overlay.
- 100% Preference for Higher Resolution over Faster Frame Rate (FPS).
- 100% Audio Channel Necessary/Helpful.

## **LCD**

- Overall Average 4.22 (5=Highest)
- Brightness/Contrast Lowest 3.87/3.97

Note: These test values represent overall averages for Low and Standard indoor light levels.

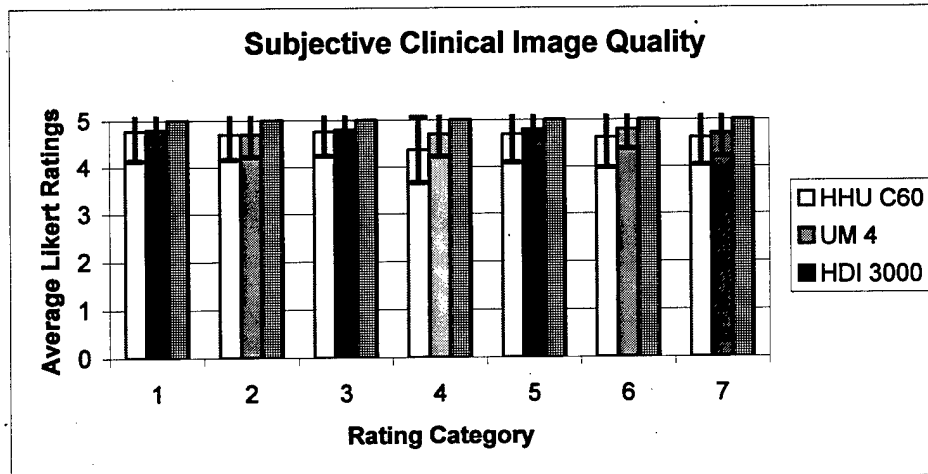
## **TRANSDUCER SIZE**

- Overall Average 3.64 for C60 (5=Highest)
  - Worked reasonably well including intercostal access.

## **EASE OF USE**

- Difficult to Evaluate because of laptop computer/software interface (temporary adaptation for this prototype)

(70 Evaluations on 10 Subjects )



- 1- Visualization of kidney/liver contour
- 2- Fluid visualization: (i.e. Rule Out significant fluid/blood in Morison's pouch)
- 3- Normal Respiratory Motion
- 4- Comparative echogenicity: (i.e. liver>kidney)
- 5- Rule Out hydronephrosis (dilated kidney)
- 6- Rule Out significantly dilated biliary ducts
- 7- Gall bladder visualization

Scale: 5.....4.....3.....2 .....1  
 Good Moderate Fair Slightly Useful Not Useful

*Clinical evaluation of blunt abdominal trauma at Harborview Trauma Center (a level 1 trauma center) using protocols developed in Task 1. Preliminary evaluation of thoracic trauma.*

Study with Trauma Patients at Harborview Medical Center  
 using the HDI-3000

**Description:**

The model for this study is to image trauma patients at Harborview Medical Center. An HDI-3000 is sited in the emergency trauma area. The emphasis is abdominal trauma with particular attention to fluid volume (hemoperitoneum) plus pleural and pericardial fluid and detection of bleeding source (organ trauma). Patients who are admitted for possible internal bleeding are scanned during the short interval the patient is being evaluated or prepared for anesthesia or prior to diagnostic peritoneal lavage (DPL) or before or after CT scan. All scanning is performed in a manner to avoid interfering with the normal management of the patient. This is a team effort between the Department of Surgery, Trauma Center Emergency room, Department of Radiology, and Department of Anesthesiology.

The original plan to evaluate blunt abdominal trauma (BAT) by detecting hemoperitoneum and correlation with diagnostic peritoneal lavage (DPL), CT, and surgical findings remains as the



central focus. In addition, an attempt to detect the bleeding source is being made (as clinically feasible) specifically to note US evidence of trauma to the liver, spleen and kidney.

Other applications of diagnostic ultrasound (US) are also being explored that can be applied to battlefield and remote applications (see Task 1 Protocols). Nonconventional applications using US in remote settings where more conventional diagnostic modalities are not available are being explored in order to increase the diagnostic capability of the portable hand-held US unit. Some of these applications include cardiac tamponade, pneumothorax, ectopic pregnancy, fracture, and hemothorax. Studies already performed at Harborview include: abdominal trauma with hemoperitoneum, organ trauma, long bone fracture, atlanto-occipital dislocation (AOD), pericardial effusion, and abdominal fluid.

Blunt Abdominal Trauma (BAT) was evaluated with ultrasound (US) at Harborview Medical Center (HMC) in Seattle beginning 14 July 1997. This was a cooperative effort between the DARPA project and the DARPA/TRP project at HMC that was comparing US with diagnostic peritoneal lavage (DPL). Our primary focus was on the detection of intra-abdominal fluid (hemoperitoneum) in patients with BAT.

Several hundred trauma patients were evaluated with US and DPL (see HMC/BAT Appendix B). The results from US and DPL were found to be comparable (Appendix B) with an accuracy of 97-98%. Ultrasound does offer the advantage of being a non-invasive procedure and does not require a laboratory offering an advantage in remote settings such as the battlefield.

#### **Task 7 - Clinical Evaluation: Deployed Setting**

*Clinical evaluations will be performed using the integrated system (i.e., hand-held ultrasound, codecs, HMD, and telecommunications) in at least two of the following scenarios: (1) military maneuver, (2) an at-sea application, (3) remote emergency/disaster simulation, (4) deployed military setting.*

Because of the delay of the self-contained battery powered hand-held US unit (SonoSite 180) until September 1999, additional field-testing as planned in Task 7 has not as yet occurred. An early model of the SonoSite 180 was tested at NASA/JSC in June 1999. Dr. Carter demonstrated the 'ureteral jets', using the power Doppler mode, to Dr. Billica, Chief of Medical Operations, NASA/JSC.

The field-testing is in the planning stage with HHU's with telemedicine capability (SonoSite 180) being deployed to the Army (Col. Chacko, Brooke Army Medical Center, and UW/Madigan/Fort Lewis), and to the Air Force (Maj. Freckleton, Lackland AFB). Additional funding will be needed in order to complete the proposed field-testing.

During the delay, extensive testing was performed using the DARPA C60 prototype both with and without telemedicine (see above and Appendices A & B). Further analysis of the previous field-testing was performed (see Appendices). The preliminary evaluation of the SonoSite 180 has shown good diagnostic quality and relative ease of use.

## **KEY RESEARCH ACCOMPLISHMENTS**

- Development of the DARPA C60 Prototype Hand-held Ultrasound (US) Unit.
- Development and Delivery of the SonoSite 180 Portable Self-Contained Commercially Available Diagnostic US unit with Telemedicine Capability.
- Clinical Protocols for Remote Ultrasound Examinations.
- Expansion of Diagnostic US Applications for Unique Remote Diagnosis e.g. Fracture.
- Telemedicine Testing using MPEG and Wavelet Compression.
- Integration of Portable US Systems with Telemedicine and Clinical Testing.
- Testing of Wide Range of Bandwidths, Transmission Modes, and Compression Ratios for Diagnostic Telemedicine and Remote Direction.
- Testing Ability to Direct Remote US Examination from Level of Novice to Expert.

## REPORTABLE OUTCOMES

- Manuscripts, Abstracts, Presentations

Stewart BK, Carter SJ, Langer SG. Evaluation of Compressed Video Ultrasound Image Quality Using the Advanced Communications Technology Satellite. *Radiology* 1997; 205P, 524.

Andrew RK, Stewart BK, Langer SG, Stegbauer KC. Wavelet Compression of Ultrasound Video Streams for Teleradiology. *IEEE International Conference on Information Technology Applications in Biomedicine* 1998, pp. 15-19.

Stewart BK, Carter SJ, Langer SG, Andrew RK. Compressed Ultrasound Video Image Quality Evaluation Using a Likert Scale and Kappa Statistical Analysis. *Proc. SPIE* 1998; 3335: 365-377.

Stewart BK, Carter SJ, Langer SG, Andrew RK. Evaluation of Compressed Ultrasound Video Image Quality Using a Likert Scale and Kappa Statistics. *Radiology* 1998; 209P, 244.

Langer SG, Stewart BK, Andrew RK, Carter SJ. World Wide Web-based Tool for Subjective Human Observer Ranking of Compressed Ultrasound Images. *Radiology* 1998; 209P, 534. *RSNA Scientific Exhibit*.

Andrew RK, Stewart BK, Langer SG, Stegbauer KC. A Novel Wavelet Compression Codec for Pre-scan Converted Diagnostic Ultrasound Video. *Radiology* 1998; 209P, 516. *RSNA Scientific Exhibit*.

Stegbauer KC, Andrew RK, Langer SG, Carter SJ, Stewart BK. The Use of Fourier Domain Subsampling for Real-time Wavelet Compression of Ultrasound Video. *Radiology* 1998; 209P, 515. *RSNA Scientific Exhibit*.

Stewart BK, Carter SJ, Cook JN, Abbe BS, Pinck D, Rowberg AH. Application of the Advanced Communications Technology Satellite to Teleradiology and Real-time Compressed Ultrasound Video Telemedicine. *Journal of Digital Imaging*, 1999; 12:68-76.

Langer SG, Stewart BK, Andrew RK. A Web based tool for Subjective Observer Ranking of Compressed Medical Images. *Proc. SPIE* 1999; 3663: 225-9.

Andrew RK, Stewart BK, Langer SG, Stegbauer KC. A 3-D Wavelet-based Codec for Lossy Compression of Pre-scan Converted Ultrasound Video. *Proc. SPIE* 1999; 3658: 396-405.

Stegbauer KC, Stewart BK, Langer SG, Andrew RK. The Use of Fourier Domain Subsampling for Real Time Wavelet Compression of Ultrasound Video. *Proc. SPIE* 1999; 3658:493-501.

Carter SJ, Stewart BK, Kushmerick MJ, et al. Diagnostic Ultrasound and Telemedicine Utilization in the International Space Station. *Space Technology and Applications International Forum* (in press).

Martin RW, Carter S, Vaezy S, Stewart BK, Schmiedl U, Rice MM, Freckleton M, Pflugrath L, Crum L. Miniature Digital Ultrasound for Mobile and Remote Imaging. Military Medicine 1999; (in press).

- The success of this project has resulted in the formation (spin-off) of a separate corporation from ATL (SonoSite) to market a commercially available model of the HHU with a wide range of clinical applications.
- ATL/SonoSite have patents and licenses and FDA approval for the Portable Ultrasound (SonoSite 180) Unit.
- Development of Wavelet Compression Techniques for US Telemedicine.
- Funding applied for with NASA for application of portable US/Telemedicine in Space.

## CONCLUSIONS

The successful development of an easily portable high quality sophisticated diagnostic ultrasound system with telemedicine capability does have significant importance and medical implications. The technological advances made will benefit the soldier in terms of bringing the image acquisition and diagnostic device to the soldier regardless of location rather than having to transport the soldier to the device. This will allow the 'point of service' diagnosis to be made in the military battlefield. This can save precious time during the so-called 'golden hour' which can be lifesaving for the soldier.

This self-contained battery powered US unit (SonoSite 180) weighs about 5 lb. and has high quality diagnostic imaging capability including color power Doppler. A primary goal of the DARPA/USAMRMC project was to detect intra-abdominal bleeding (hemoperitoneum) from blunt abdominal trauma (BAT). The portable unit with telemedicine can be used to make a wide variety of diagnoses in remote settings including bleeding, kidney stone, gall bladder disease, vascular disruption, pneumothorax, shrapnel, aortic aneurysm, cardiac tamponade, and even fractures (see Soldier/Appendix B).

The ability to get the image acquisition and diagnostic device to the soldier (regardless of location) along with the telemedicine capability (when needed) not only allows a more rapid evaluation of the soldier in the field or during transport, but also allows remote diagnostic capability by experts. The US examination can also be 'directed' remotely by experts when needed.

Telemedicine has been tested using a variety of compression techniques (including MPEG & wavelet) and modalities varying from the NASA ACTS Mobile Satellite Terminal (AMT) to the Internet (See Appendix B). Remote ultrasound examinations have been directed with success using personnel from the level of novice to expert. It is envisioned that this type of system may become standard in remote applications such as military medics, helicopter transport, triage, civilian disaster settings, 911 vehicles, and for space missions.

Future work will involve testing of the SonoSite 180 in military settings and with telemedicine using military communication systems. (It was hoped that this could be performed before the completion of this grant but the development and delivery of the SonoSite 180 took longer than anticipated.) The 180 unit did have improved capability and features (e.g. keyboard, changeable scan heads) beyond the original envisioned HHU.

### *"SO WHAT SECTION"*

One concern from a scientific and medical standpoint is that diagnostic ultrasound (US) is often complicated to perform and to interpret. US trauma exams need to be made by a well-trained care provider. This requires adequate training of medics and application of telemedicine when needed. Remote interpretation and direction by experts and use of 3D imaging may be necessary or

helpful, depending upon the clinical setting. Simplification of the controls (e.g. pre-set TGC in the 180) and clinical protocols are also useful for remote US diagnosis.

There is increased size of the SonoSite 180 compared with the DARPA C60 prototype to accommodate the keyboard and interchangeable scanheads. This was seen as a compromise that did add some additional features but did make the unit larger than the DARPA prototype (with the beam-forming electronics in the scanhead).

The power Doppler feature is very helpful and easy to use but many US experts would like to see directional color Doppler added at some point for additional vascular evaluation. Also requested is a smaller scanhead for intercostal access.

## REFERENCES

- [Alt91] Altman DG. Practical Statistics for Medical Research (Chapman and Hall, London), 396-439 (1991).
- [Andr98] Andrew RK, Stewart BK, Langer SG, Stegbauer KC. Wavelet Compression of Ultrasound Video Streams for Teleradiology. IEEE International Conference on Information Technology Applications in Biomedicine 1998, pp. 15-19.
- [Andr99] Andrew RK, Stewart BK, Langer SG, Stegbauer KC. A 3-D Wavelet-based Codec for Lossy Compression of Pre-scan Converted Ultrasound Video. Proc. SPIE 1999; 3658: 396-405.
- [Flei81] Fleiss L. Statistical Methods for Rates and Proportions (John Wiley & Sons, New York), 213-235 (1981).
- [Fors92] Forster R, Pillasch J, Zielke A, Maleswki U, Rothmund M. Ultrasonography in Blunt Abdominal Trauma: Influence of the Investigators' Experience. The Journal of Trauma, 1992; 34(2): 264-9.
- [Kimu91] Kimura A, Otsuka T. Emergency Center Ultrasonography in the Evaluation of Hemoperitoneum: A Prospective Study. The Journal of Trauma, 1991; 31(1): 20-3.
- [Ma95] Ma OJ, Mateer JR, Ogata M, Kefer MI?, Wittmann D, Aprahamian C. Prospective Analysis of a Rapid Trauma Ultrasound Examination Performed by Emergency Physicians. The Journal of Trauma, 1995; 38(6): 879-85.
- [Meet88] Meetz HK, Bebeau MJ and Thoma SJ. The validity and reliability of a clinical performance rating scale. J. Dent. Educ, 1988; 52(6): 290-297.
- [Merr94] Merrill JM, Camacho Z, Laux LF, et al. Uncertainties and ambiguities: measuring how medical students cope. Med. Educ., 1994; 28(4): 316-322.
- [Roth93] Rothlin MA, Naf R, Angwerd M, Candinas D, Frick T, Trentz O. Ultrasound in Blunt Abdominal and Thoracic Trauma. The Journal of Trauma, 1993; 34(4): 488-95.
- [Rozy93] Rozycki GS, Ochsner MG, Jaffin JH, Champion HR. Prospective Evaluation of Surgeons' Use of Ultrasound in the Evaluation of Trauma Patients. The Journal of Trauma, 1993; 34(4): 516-26.
- [Stew95] Stewart BK, Carter SJ, Rowberg AH. Application of the Advanced Communications Technology Satellite for Teleradiology and Telemedicine. Proc SPIE 1995; 2435: 210-219.
- [Stew96] Stewart BK, Carter SJ, Rowberg AH, Cook J, Abbe B, Pinck D. Real-time Compressed Video Ultrasound Using the Advanced Communications Technology Satellite. Proc SPIE 1996; 2711: 194-204.

[Stew97] Stewart BK, Carter SJ, Langer SG. Evaluation of Compressed Video Ultrasound Image Quality Using the Advanced Communications Technology Satellite. Radiology 1997; 205P: 524.

[Stew98] Stewart BK, Carter SJ, Langer SG, Andrew RK. Compressed Ultrasound Video Image Quality Evaluation Using a Likert Scale and Kappa Statistical Analysis. Proc. SPIE 1998; 3335: 365-377.

[Stew99] Stewart BK, Carter SJ, Cook JN, Abbe BS, Pinck D, Rowberg AH. Application of the Advanced Communications Technology Satellite to Teleradiology and Real-time Compressed Ultrasound Video Telemedicine. Journal of Digital Imaging, 1999; 12:68-76.



## BIBLIOGRAPHY

- Stewart BK, Carter SJ, Langer SG. Evaluation of Compressed Video Ultrasound Image Quality Using the Advanced Communications Technology Satellite. *Radiology* 1997; 205P, 524.
- Andrew RK, Stewart BK, Langer SG, Stegbauer KC. Wavelet Compression of Ultrasound Video Streams for Teleradiology. *IEEE International Conference on Information Technology Applications in Biomedicine* 1998, pp. 15-19.
- Stewart BK, Carter SJ, Langer SG, Andrew RK. Compressed Ultrasound Video Image Quality Evaluation Using a Likert Scale and Kappa Statistical Analysis. *Proc. SPIE* 1998; 3335: 365-377.
- Stewart BK, Carter SJ, Langer SG, Andrew RK. Evaluation of Compressed Ultrasound Video Image Quality Using a Likert Scale and Kappa Statistics. *Radiology* 1998; 209P, 244.
- Langer SG, Stewart BK, Andrew RK, Carter SJ. World Wide Web-based Tool for Subjective Human Observer Ranking of Compressed Ultrasound Images. *Radiology* 1998; 209P, 534. *RSNA Scientific Exhibit*.
- Andrew RK, Stewart BK, Langer SG, Stegbauer KC. A Novel Wavelet Compression Codec for Pre-scan Converted Diagnostic Ultrasound Video. *Radiology* 1998; 209P, 516. *RSNA Scientific Exhibit*.
- Stegbauer KC, Andrew RK, Langer SG, Carter SJ, Stewart BK. The Use of Fourier Domain Subsampling for Real-time Wavelet Compression of Ultrasound Video. *Radiology* 1998; 209P, 515. *RSNA Scientific Exhibit*.
- Stewart BK, Carter SJ, Cook JN, Abbe BS, Pinck D, Rowberg AH. Application of the Advanced Communications Technology Satellite to Teleradiology and Real-time Compressed Ultrasound Video Telemedicine. *Journal of Digital Imaging*, 1999; 12:68-76.
- Langer SG, Stewart BK, Andrew RK. A Web based tool for Subjective Observer Ranking of Compressed Medical Images. *Proc. SPIE* 1999; 3663: 225-9.
- Andrew RK, Stewart BK, Langer SG, Stegbauer KC. A 3-D Wavelet-based Codec for Lossy Compression of Pre-scan Converted Ultrasound Video. *Proc. SPIE* 1999; 3658: 396-405.
- Stegbauer KC, Stewart BK, Langer SG, Andrew RK. The Use of Fourier Domain Subsampling for Real Time Wavelet Compression of Ultrasound Video. *Proc. SPIE* 1999; 3658:493-501.
- Carter SJ, Stewart BK, Kushmerick MJ, et al. Diagnostic Ultrasound and Telemedicine Utilization in the International Space Station. *Space Technology and Applications International Forum* (in press).

Martin RW, Carter S, Vaezy S, Stewart BK, Schmiedl U, Rice MM, Freckleton M, Pflugrath L, Crum L. Miniature Digital Ultrasound for Mobile and Remote Imaging. *Military Medicine* 1999; (in press).

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## **APPENDIX A**

Pages: 15  
 Text Words: 3531  
 Abstract: 143  
 References: 39  
 Figures: 5  
 Tables: 2  
 Photos: 4  
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**Key Words:**  
 ultrasound, imaging ,  
 abdominal, trauma,  
 portable, scanner

**Abstract**

The utility of a miniature ultrasound unit that would be highly transportable and easily applied was explored in the context of combat casualty care. Such a unit would logically aid in triage and early trauma decisions. A consortium of three major corporations and a university identified medical applications and developed a prototype unit. Utilizing state of the art integrated circuit techniques and ultrasound imaging methods, the major electronics were built into the probe itself, a new concept. This probe assembly is 3.4 x 7.8 x 16.2 cm and weighs 351g. It drives an external 12.7-cm liquid crystal display and provides an output compatible with telemedicine linkages. Early evaluation by experts have rated the image quality to be similar to a mid-range clinical diagnostic ultrasound machine and the quality highly usable for diagnosing critical trauma conditions such as the presence of abdominal-free fluid.

## Introduction

The concept of bringing trauma care closer to the time and location of injury has evolved since the 1980's (1-4). This is in contrast, but also in coordination, with more rapid "scoop and run" methods not always possible (5,6). A number of novel concepts have been proposed and/or being investigated (2) including telemedicine (7) and telepresence surgery (8). Also during this time period, the value of ultrasound imaging for aiding in triage and diagnostic decisions has become apparent (4), specifically, its use in blunt trauma hemorrhage assessment (9-16). Here it is increasingly being employed to replace diagnostic peritoneal lavage, because it is more rapid, sensitive, and avoids the complications of abdominal puncture (13,16).

There are also a number of other important ultrasound (US) uses in trauma. Its use in assessing penetrating injury is less documented but it has been recommended in chest wounds (12,15,17-19). It is one of the key diagnostic tools for detecting pericardial effusion (20,21) and treating cardiac tamponade by US guided needle aspiration (pericardiocentesis) (28). Ultrasound is widely employed in echocardiography to visualize the left and right ventricles (22). It, however, has not been broadly applied in trauma to assess cardiac status (e.g. cardiac contraction, ventricular volumes and filling). The detection of air embolism and possibly pulmonary hemorrhage in the primary blast injury with ultrasound may also prove useful. Again, there has been little testing of this, but ultrasound has been widely employed in civilian surgery to detect air embolism (23) and in deep-sea diving to detect gas embolism associated with bends (24). There is also a body of supportive literature in US detection of pneumothorax (25-27) and hemothorax (28) also can be consequences blast injury (29). Foreign bodies (e.g. glass or sharp shrapnel) which become imbedded adjacent to critical areas (heart, aorta, lung or spine) can be life threatening. Knowledge of their presence may facilitate an evacuation or object removal plan to avoid causing increased or life threatening damage. Ultrasound detection of foreign objects is well recognized. The use of US in assessment of vascular integrity is a standard tool in many clinics, but not necessarily in life threatening situations. Finally, there are a variety of disease conditions such as acute appendicitis and ectopic pregnancy that can be of emergent concern. Although these conditions may not generally be of high combat incidence, the wide deployment

of personnel at remote sites for long periods bring these possibilities into prominence. Ultrasound is widely used for diagnosis of these conditions in hospitals.

A major difficulty in the trauma environment and in mobile applications is the size, weight, and awkwardness of the standard commercial US units. The current clinical US machines need to be electrically connected to the power outlet, require several minutes of internal calibration before they are ready to operate after they are turned on, and they occupy a large space and displace trauma team members during the ultrasound scanning. Their numerous controls make them difficult to use. These are all highly undesirable features. Furthermore, repeated US imaging (e.g. during the first few hours after ER arrival) is impeded by the difficulty of moving conventional large imaging machines to the patient. Logically, having a portable US unit on location should facilitate such imaging.

To address the above difficulties in using conventional US machines for combat casualty care, a consortium consisting of Advanced Technology Laboratories (ATL) (Bothell, WA), Harris Semiconductor Inc. (Palm Bay, FL), VLSI Technology Inc. (San Jose, CA), and the University of Washington (UW) (Seattle, WA) was formed. This consortium was under a DARPA sponsored Technology Reinvestment Project (TRP) in combination with a DARPA Telemedicine/Remote Portable US project for the purpose of investigating the following hypotheses and questions: 1. Using the advanced techniques of digital ultrasound and very large scaled integration, could a small hand held ultrasound unit be developed which would have imaging quality approaching today's midrange ultrasound machines and be usable in the proposed application? 2. Could a small image display, which would be necessary for a portable unit, provide adequate image visibility for diagnosis in the various environmental conditions anticipated? 3. Could telemedicine play a role in the utility of such a device in forward echelons or remote sites, both for remote diagnosis and remote directing of the image acquisition? 4. And finally, what medical utility would such a device have?



## Methods and Results:

*Initial Prototype Imaging Unit.* The corporate team addressed the first question, while the UW led in the investigation of the other questions. ATL applied their knowledge in high definition digital ultrasound to develop an overall system design, fabrication, and testing plan. Based on their experience, it was believed that there would be a major advantage in image quality and robustness if the device was designed completely using digital techniques. Therefore, custom large scaled integrated circuits were defined utilizing 0.35-micron technology (very high circuit component density). They were developed and fabricated by Harris Semiconductor and VLSI for specific circuit functions. A curvilinear ultrasound transducer (similar to the ATL C4-2) was chosen for the probe because of its ability for abdominal imaging. A separate corporation SonoSite Inc. (Bothell, WA) was created by ATL midway through the project to further develop and market small and portable ultrasound equipment. SonoSite joined the consortium and took over the main ATL role in 1998. DARPA prototypes were then assembled, bench tested, and software was developed and optimized.

The DARPA prototype that was built for the initial testing, HHU C60, consists of four components: (1) a probe consisting of a C60 curvilinear transducer with all the major imaging components built within it; (2) a display box and components for communicating with the transducer system and a laptop computer; (3) a power supply for the display and probe; and (4) a laptop computer with software for controlling the imaging parameters. The size of the unit compared to two other conventional ultrasound units is shown in Fig. 1 and in a close up view Fig. 2. The probe weighs 351 g and its dimensions are (3.4 x 7.8 x 16.2 cm) and the circumferential distance of the arc of the curvilinear transducer array is 70mm. The display is a 12.7 cm diagonally (5 ") liquid crystal display (LCD). This early prototype packaging (4 components) is not suitable for use in the emergency room , therefore, no studies could be conducted in that environment. However, the imaging ability and overall performance of the unit was assessed in several ways.

Overall performance for diagnosis was evaluated with 10 volunteer subjects (9 normal and 1 peritoneal dialysis patient) by 4 radiologists and 2 expert sonographers. Comparisons were made with it to a high level (ATL HDI 3000) and midrange (ATL UltraMark 4) imaging units. A Likert scale (clinical subjective preference) of 1-5, with 5 representing the best, was used to rate the units. Results are shown in Fig. 3A & C with some example images in Fig. 4. The average of all 7 categories for the three units for *overall imaging* was: HHU C60 - 4.65/5.0, UM 4 - 4.76/5.0, and the HDI 3000 - 5.0/5.0, Fig. 3A. Note that these are all very high and acceptable scores for the intended use. The *transducer size*, the *ease-of-use* and the *examination time required* are given in Fig. 3C. The *ease-of-use* was low at 3.5/5.0, but this was mostly due to the current awkwardness of the laptop controlling the prototype unit, which will be corrected in future with an integrated system. All units were noted to do well for the detection of abdominal fluid. The HHU C60 easily detected fluid in all 4 abdominal quadrants including pelvis and gutters for the dialysis patient. An absent kidney was correctly identified in one "normal" subject. Renal Cysts and Calculi in another patient were detected. Based on the expert's judgement of the image quality, hydronephrosis is easier to rule out than dilated biliary ducts, respiratory motion is easily detected, and comparative echogenicity of liver versus kidney tends to be the subtlest differentiation. All examiners were surprised and pleased with the quality of the images of the HHU C60. They felt it very acceptable for diagnostic purposes. They didn't mind the size of the probe as it did not interfere with diagnosis, even though more rib shadowing occurred than with the smaller probe on the UM 4. The only complaint was the cumbersomeness of the human interface for controlling the imaging parameters as mentioned earlier. Clearly this needs improvement and will be resolved. However, the prototype represents an interim step in the development and not the final unit. All the radiologists were quite excited about the concept of such a small unit and felt it really would be useful in ambulatory situations.

*Display and Human Interface.* Early on a question arose regarding whether a small display (necessary for a portable unit) would provide enough resolution for making diagnostic decisions? This question was jointly studied between the UW and ATL. Available display types were critiqued and two prototype displays and one head-mounted display (HMD) were evaluated: (a) 14 cm (5.5") Liquid Crystal Display (LCD) (320 x 240 pixels) with < 128 gray levels and 64 colors, (b) 10 cm (4") LCD (160 x 234 pixels) 64

gray levels, and (c) binocular HMD with 320 x 200 pixel resolution for each eye with estimated 256 gray levels and 24 bit color. These displays were studied by connecting them to an HDI 3000 unit. Ultrasound experts then imaged volunteers using the display to guide them. Ratings were made according to the Likert scale mentioned earlier and shown in Fig. 3A. The 14 cm display was evaluated by 20 ultrasound experts, the 10 cm display by 12 experts and the HMD by 17 experts. All of the experts had at least 5 years' experience and 10 or more was the average. The HMD has a cover for reducing the effects of ambient light but the cover does interfere with simultaneous display and surrounding environment viewing, therefore, it was tested with and without the cover. The average clinical impression ratings for these three units were respectively: 4.3/5.0, 4.5/5.0, and 4.9/5.0 with the cover and 4.2/5.0 without the cover. The favorable finding was that the experts found the small screens quite acceptable for making diagnostic decisions. The 14-cm display was actually felt larger than necessary by many evaluators. The image quality did deteriorate rapidly at viewing angles that were not at 90° to the screen. The correct viewing angle is always maintained with the HMD, so it does not suffer from that problem, but the HMD has other shortcomings. It is fragile and cumbersome to store and to put on, therefore, If it is a viewing device only for ultrasound imaging this adds extra manipulations. If on the other hand a HMD was part of other equipment being used, then it may well be practical. Changes are occurring rapidly in small displays and some of the shortcomings of earlier units are being overcome. In fact, the display incorporated into the HHU-C60 performs much better than the earlier units evaluated above with results given in Fig 3B.

Since the ambient light environment that the display is viewed in effects its visibility, ambient light conditions were measured in a variety of places utilizing an optical power meter (840-C, Newport CO. Irvine, CA). The measurement revealed 5-6 orders of magnitude variation in light intensity (Table 1). Further, because there was such a divergence in the outside light, we measured it with the sensor pointing physically up or down. That made quite a difference. The ultrasound scanning room and radiology reading room are purposely kept at dim level because it aids image viewing. In contrast, the operating room and triage area have more light because it is advantageous for the functions performed there. Shading the screen and turning its brightness up are all actopms that can be done to aid in visualizing displays in many cases. However, if the image is adjusted too bright the gray features of the image can be lost.

*Telemedicine and Remote Direction:* Prior to the availability of the HHU -C60, a number of telemedicine studies were conducted using US. First, we investigated the application of the NASA Advanced Communications Technology Satellite (ACTS) to teleradiology using the Jet Propulsion Laboratory (JPL) (Pasadena,, CA) developed ACTS Mobile Terminal (AMT) uplink. In this experiment, bi-directional 128, 256 and 384 kbps satellite links were established between the ACTS/AMT, the ACTS in geosynchronous orbit, and the downlink terrestrial terminal at JPL. A terrestrial Integrated Digital Services Network (ISDN) link was established from JPL to the UW Department of Radiology to complete the bi-directional connection. Ultrasound video imagery was compressed in real-time using video codecs adhering to the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) Recommendation H.261.

A simulated MASH environment was arranged at Madigan Army Medical Center (Ft. Lewis, WA). Twelve soldiers were imaged with an ATL HDI-3000 ultrasound machine in the MASH triage tent. Video lines were run from that tent to the AMT to ACTS and the compressed video images were viewed at the UW in Department of Radiology in real-time. A 384 kbps data rate was used throughout the simulation. Of the 12 presumed normal Special Forces volunteers arose one liver lesion and one gallstone.

The Hawaiian portion of the ACTS/AMT experiments demonstrated: mobile at-sea transmission with the Navy at Pearl Harbor, (Honolulu, HI) relay transmission between a ground station in Micronesia and the ACTS/AMT at Tripler Army Medical Center (Honolulu, HI) and disaster simulation with PacSpace and the Hawaii Civil Defense. Again, the static and real-time video imagery was downlinked from the ACTS to the JPL and transmitted to the UW Radiology Department as described above. The findings of the remote testing with the ACTS/AMT did demonstrate that good quality diagnostic information could be achieved at a data rate of 384 kbps. There was noted to be a "shoulder" with a significant improvement in diagnostic quality between the 128/256kbps and the 384 kbps.

We have also used the Internet and POTS (plain old telephone system) to transmit the real-time US video. During this period we built up a small multimedia server for connecting an ultrasound system to a local area network (Ethernet) and the Internet. A laptop PC uses a video capture PCMCIA Card to acquire ultrasound video. The video is transmitted using Microsoft NetMeeting teleconferencing software with H.323 compression. We have also used the 8x8 ViaTV Phone with H.324 compression. The HHU C60 was tested with this system with the interactive TV Phone link.

We found there was a slight degradation in the compressed images (Table II). This small degradation did not interfere with diagnosis. The value of the feedback an examiner at the patient's side obtains from the remote expert by telemedicine was interesting. It was rated quite different depending on whether the patient-examiner was a novice or a moderate-to-expert ultrasound examiner. People who already are moderate-to-expert could communicate with the remote expert by voice commands alone. Therefore, the value of the remote expert being able to see the location of the probe on the patient via video images was rated low for the expert (2.63/5.0) but much higher (4.8/5.0) for the novice. On the other hand, the value of the graphic overlay was rated fairly similarly between the novice and the expert. Finally, the audio channel was rated at 5.0/5.0 by either experienced examiners and felt absolutely necessary for this study. In comparing compression-decompression methodology for transmitting the images to the remote location, higher resolution in the images was preferred over faster frame rate. The telemedicine linkage proved valuable both for aiding in directing of the remote US examination and in the clinical diagnosis by remote experts as needed.

*Medical Utility:* Based on the prototype unit imaging findings, it is considered to be very usable in most of, if not all, of the life threatening situations mentioned in the introduction. However, prior to the availability of the HHU C60 prototype, we did study whether an ultrasound probe designed more for abdominal imaging could be used for making life threatening cardiac assessment. Therefore, in 6 normal, 5 dilated cardiomyopathy, and 5 coronary artery disease patients, an abdominal ATL C4-2 probe and HDI 3000 was used to image the heart. An experienced cardiac ultrasonographer was asked whether the quality of the cardiac images from these subjects was of high enough quality to answer whether: 1. The heart was

beating?; 2. The heart was filling and emptying?; 3. Whether the heart function was within the normal limits? and 4. If the patient had pericardial effusion would it be detectable? The answers were respectively, 1. yes 100%; 2. yes 94% - maybe 6%; 3. yes 94% - maybe 6% ; and 4. yes 75% - maybe 25%. Based on the image quality of the images obtainable with the HHU C60 (rated slightly less than the HDI 3000 (Fig. 3A) we anticipate answers to the same questions for the HHU C60 would be similar to those obtained above.

There are a number of other applications in addition to uses of US for life threatening situations. Ultrasound has been applied in the area of foreign body detection (30). In the military its use in the detection and locating shrapnel and other foreign bodies would have value (i.e. intra or extra peritoneal space). Ultrasound is particularly useful in detecting the radio translucent material where other means fail. We found that considerable skill may be needed to distinguish foreign bodies of some types from other structures that appears in the images, but some types have very characteristic signatures (31). Example, images obtained with the HHU-60 are shown in Fig. 5.

Other uses of trauma ultrasound include assessing: diaphragm puncture or rupture (32), inflammation and post surgical fluid collections, hematomas, abscesses(33-35), and determining the extent of tissue damage beyond the visually observable. For example, in the later case it may be used to determine the extent of damage in the traumatic amputation proximal to the site in order to aid in the decision of the selected region for surgical amputation (personal communication Robin Coupland, 36). Vascular damage evaluation without the use of angiography is possible with US in some cases. Color Doppler US and more recently "Power" Doppler are techniques being employed (37). There are numerous non-trauma uses for diagnostic ultrasound as well (e.g. evaluation for appendicitis, kidney stones, cardiac problems, pregnancy, and obstetrical and gynecological complications) (38).

Finally, there are some non-conventional uses of US at a remote or early echelon site where there would be no X-ray equipment. One such viable use would be to evaluate fractures or dislocations. Although, certainly more difficult than X-rays to use for this purpose, useful information can be gained. For example,

in addition to the fracture site and angulation, adjacent soft tissue evaluation such as periosteal elevation and hematoma can also be obtained.

**Comments:** The feasibility of developing small hand-held digital based US units, that can be highly portable and provide good diagnostic images, has been demonstrated. Such units have great potential for use in triage and trauma diagnosis. However, applying and reading US images in general requires considerable training and US exams in trauma need to be made by well trained and capable care providers. Through new training programs and material, it has been demonstrated that for limited use, non-imaging experts can learn to apply US to make life threatening diagnoses such as detecting free fluid in abdominal injury (39). Furthermore, telemedicine linkages can extend the capability for use at 1<sup>st</sup>/2<sup>nd</sup> echelon or remote locations where personnel may have limited US imaging training. We demonstrated that an expert can remotely direct an US examination by a novice and make a definitive diagnosis. Nevertheless, there is no substitute for training and experience particularly in time restricted diagnostic decision-making. Finally, units of this nature are becoming commercially available (e.g. Sonosite Inc., Bothell, WA) and we believe their use will be common place in the future for many of the applications discussed, as well as for many new unforeseen ones.

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#### **Reference:**

1. Trunkey DD: Trauma. Sci Amer 1983; 249(2):28-35.
2. Zajtcuk, R, Sullivan GR: Battlefield trauma care: focus on advanced technology. Milit Med 1995; 160:1-7.

3. Anderson GK: A decade of great progress in medical readiness. *Milit Med* 1990; 155(11):535-38.
4. ARPA/ONR Medical Ultrasonic Imaging Technology Workshop. Lansdowne, VA, Jan. 1995.
5. Martin TE: Resolving the casualty evacuation conflict. *Injury* 1993; 24(8):514-16.
6. Truthan CE: New tools for combat casualty care (letter, comment) *Milit Med* 1997; 162(1):vii.
7. Mun SK, Levine B, Cleary K, Dai H,: Deployable teleradiology and telemedicine for the US military. *Comput Method Program Biomed* 1998; 57(1-2):21-27.
8. Satava RM: Virtual reality and telepresence for military medicine. *Comp Biol Med* 1995; 25(2):229-36.
9. Forster R, Pillasch J, Zielke A, Malewski U, Rothmund M,: Ultrasonography in blunt abdominal trauma: influence of the investigators' experience. *J Trauma* 1992; 34 (2):264-69.
10. Bode PJ, Niezen RA, van Vugt AB, Schipper J,: Abdominal ultrasound as a reliable indicator for conclusive laparotomy in blunt abdominal trauma. *J Trauma* 1993; 34(1):27-31.
11. Liu M, Lee CH, P'eng FK,: Prospective comparison of diagnostic peritoneal lavage, computer tomographic scanning, and ultrasonography for the diagnosis of blunt abdominal trauma. *J Trauma* 1993; 35(2):267-70.
12. Rozycki GS, Ochsner MG, Jaffin JH, Champion HR,: Prospective evaluation of surgeons' use of ultrasound in the evaluation of trauma patients. *J Trauma* 1993; 34(4):516-27.
13. McKenney M, Lentz K, Nunez D, Sosa JL, Sleeman D, Axelrad A, Martin L, Kirton O, Oldham C,: Can ultrasound replace diagnostic peritoneal lavage in the assessment of blunt trauma? *J Trauma* 1994; 37(3):439-41.
14. McKenney MG, Martin L, Lentz K, Lopez C, Sleeman D, Aristide G, Kirton O, Nunez D, Najjar R, Namias N, Sosa J,: 1,000 consecutive ultrasounds for blunt abdominal trauma. *J Trauma* 1996; 40(4):607-12.
15. Rozycki GS, Shackford SR: Ultrasound, what every trauma surgeon should know. *J Trauma* 1996; 40(1):1-4.
16. Bain IM, Kirby RM, Tiwari P, McCaig J, Cook AL, Oakley PA, Templeton J, Braithwaite M,: Survey of abdominal ultrasound and diagnostic peritoneal lavage for suspected intra-abdominal injury following blunt trauma. *Injury* 1998; 29(1):65-71.



17. Knudson MM, Lewis FR, Atkinson K, Neuhaus A.: The role of duplex ultrasound arterial imaging in patients with penetrating extremity trauma. *Arch Surg* 1993; 128(9):1033-37.
18. Raimonde AJ, Rodriguez A: Priorities and diagnostic studies in the management of the injured patient. *Compr Ther* 1992; 18(4):27-32.
19. Frankel H, Rozycki GS: Ultrasound evaluation of truncal injury in Ivatury RR and Cayten CG (Eds.), *The Textbook of Penetrating Trauma*, pp 364-71. Baltimore, Williams and Wilkins, 1996.
20. Sahn DJ, Anderson F: *An Atlas for Echocardiology, Two-Dimensional Anatomy of the Heart*, pp 445-53. New York, John Wiley and Sons, 1982.
21. Cikes J: Pericardial disease in Cardiac Ultrasound. Roelandt JRJC, Sutherland GR, Iliceto S, Linker DT (Eds.), pp 552-55. Edinburgh, Churchill Livingstone, 1993.
22. Force TL, Folland ED, Aebischer N, Sharma S, Parisi A.: Echocardiographic Assessment of Ventricular Function in *Cardiac Imaging a Companion to Braunwald's Heart Disease*. Marcus ML, Schelbert HR, Skorton DJ, Wolf GL, Braunwald, E (Eds.), pp 374-401. Philadelphia, W.B. Saunders Co., 1991.
23. Maroon JC, Goodman JM, Horner TG, Campbell RL.: Detection of minute venous air emboli with ultrasound. *Surg Gynecol Obstet* 1968; 127:1236-38.
24. Thorsen E, Risberg J, Segadal K, Hope A.: Effects of venous gas microemboli on pulmonary gas transfer function. *Undersea Hyperb Med* 1995; 22(4):347-53.
25. Targhetta R, *et al*: Ultrasonic Signs of Pneumothorax: preliminary work. *J Clin Ultrasound* 1993; 21:245-50.
26. Wu R.G., *et al*: "Fluid Color" Sign: a useful indicator for discrimination between pleural thickening and pleural effusion. *J Ultrasound Med* 1995; 14:767-69.
27. Lichtenstein DA, Menu Y: A bedside ultrasound sign ruling out pneumothorax in the critically ill. Lung sliding. *Chest* 1995; 108(5):1345-48.
28. Rothlin MA, Naf R, Amgwerd M, Candinas D, Frick T, Trentz O.: Ultrasound in blunt abdominal and thoracic trauma. *J Trauma* 1993; 34(4):488-95.
29. Bellamy RF: The nature of combat injuries and the role of ATLS in their management in *Combat Casualty Care Guidelines*, Zajtcuk R, Jenkins DJ, Bellamy RF, Quick CM, Moore CC (Eds.). Office of

the Surgeon General at TMM Publications, Center for Excellence, Walter Reed Army Medical Center, pp 8-21. Washington, DC, 20307-5000, 1991.

30. Lammers R and Magill T: Detection and Management of Foreign Bodies in Soft Tissue. *Emerg Med Clin N Am* 1992; 10:767-81.
31. Vaezy S, Martin RW, Proctor AP,: Foreign body detection using ultrasound imaging. *A CD\_ROM Tutorial*, Distributed at 7<sup>th</sup> International Conference on Emergency Medicine, Vancouver BC, 1998.
32. Smithers BM, Loughlin BO, Strong RW,: Diagnosis of ruptured diaphragm following blunt trauma: results from 85 cases. *Aust. N.Z. J. Surg* 1991; 61:737-41.
33. Parrini M, *et al*: Ultrasound examination of haematomas after total hip replacement. *Intl Orthop* 1988; 12:79-82.
34. Hurvitz E, Ellenberg M, Lerner AM, Pope S, Wirthlin L,: Ultrasound imaging of residual limbs: new use for an old technique. *Arch Phys Med Rehabil* 1989; 70:556-58.
35. Harris RD, Simeon JF, Mueller PR, Butch RJ,: Portable ultrasound examinations in intensive care units. *J Ultrasound Med* 1985; 4:463-65.
36. Coupland, RM: *War Wounds of Limbs - Surgical Management*, Butterworth Heinemann, Ltd. Linacre House, Oxford, Jordon Hill, 1993.
37. Kohler TR, Andros G, Porter JM, Clowes A, Goldstone J, Johansen K, Raker E, Nance DR, Strandness DE Jr,: Can duplex scanning replace arteriography for lower extremity arterial disease? *Ann Vasc Surg* 1990; 4(3):280-87.
38. Rumack CM, Wilson SR, Charbonea JW (Eds.), *Diagnostic Ultrasound Volumes I, II*. Mosby Year Book, St. Louis, MO, 1991.
39. Heller M, Jehle D: *Ultrasound in Emergency Medicine*. Philadelphia, W.B. Saunders Co., 1995.

**Figure Captions:**

Figure 1. DARPA HHU C60 prototype contrasted with two commercial imaging systems marketed by ATL.

Figure 2. Close up view of the HHU C60 probe assembly (held in an investigators hand) and the display unit.

Figure 3. The results of comparing various image and imaging unit features of the HHU C60 to ATL clinical units HDI 3000 and UltraMark 4.

Figure 4A. Image of normal liver acquired with the HHU C60. The probe is located at the top of image.

Figure 4B. Image of the liver of the peritoneal dialysis patient with fluid (dark region) surrounding the Liver acquired with the HHU C60.

Figure 5. Images of foreign bodies within in vitro swine leg. Transducer position is at the top of the image. The reverberation echoes sometimes referred, as comet tails are characteristic of bullets or other metal objects. The plastic mine appears as bright surface when the transducer is aligned fairly perpendicular to it with a dark shadow behind it due to attenuation of the US. The feces similarly have a bright surface, thought to be due to reflection entrapped air. A dark shadowing occurs behind them due the high attenuation. Other highly contaminated materials (e.g. dirt or wood) have similar characteristics.

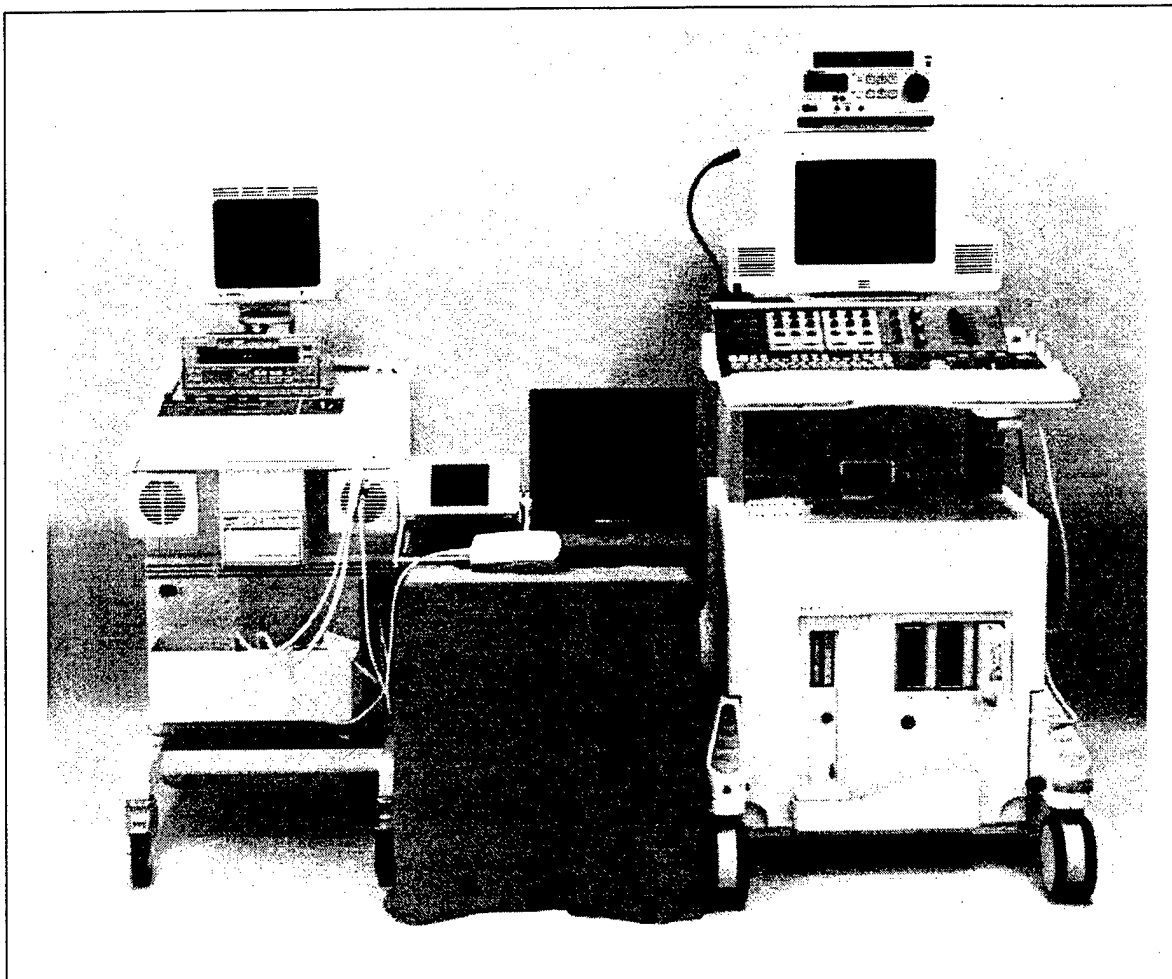


Figure 1. DARPA HHU C60 prototype contrasted with two commercial imaging systems marketed by ATL.

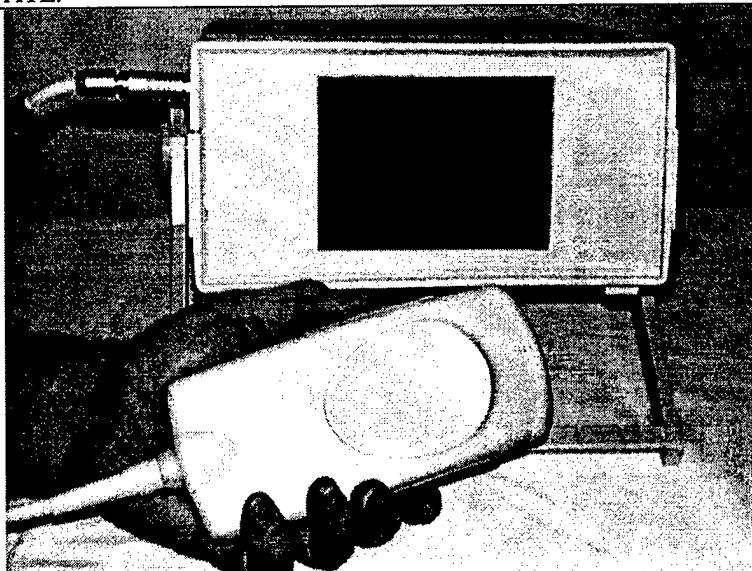
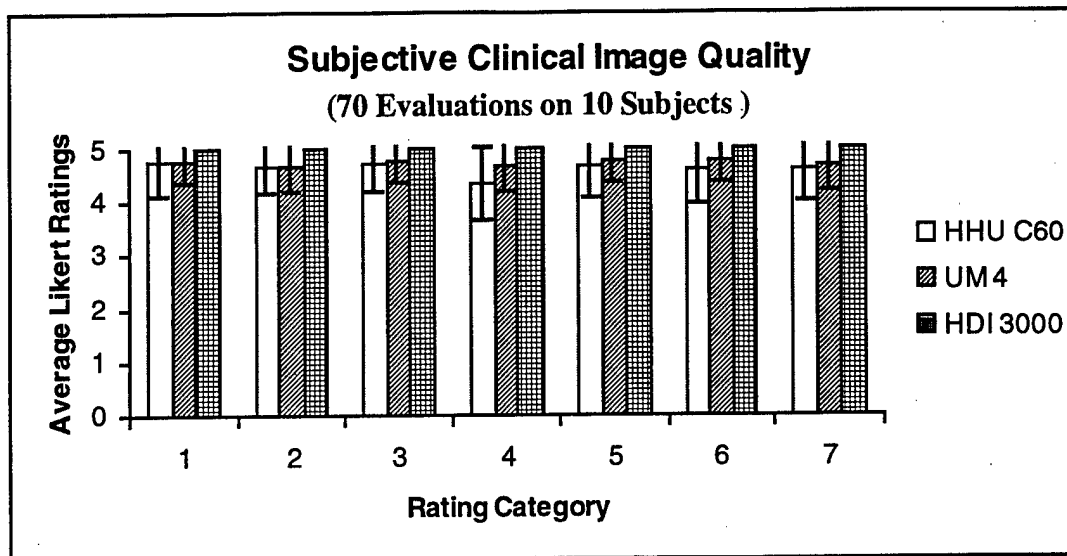


Figure 2. Close up view of the HHU C60 probe assembly (held in an investigator's hand) and the display unit.

### A. Comparison of Hand Held Unit to Two Conventional Imaging Units: ATL Ultramark 4 (UM4) and HDI 3000



- 1- Visualization of kidney/liver contour
- 2- Fluid visualization: (i.e. Rule Out significant fluid/blood in Morison's pouch)
- 3- Normal Respiratory Motion
- 4- Comparative echogenicity: (i.e. liver>kidney)
- 5- Rule Out hydronephrosis (dilated kidney)
- 6- Rule Out significantly dilated biliary ducts
- 7- Gall bladder visualization

Scale: 5.....4.....3.....2 .....1  
 Good      Moderate      Fair      Slightly Useful      Not Useful

### B. Evaluation of the Liquid Crystal Display in the Hand Held Unit (Mean±STD)

Viewing Angle Off Axis	4.3 ± 0.6
Diagnostic Quality and Resolution	4.3 ± 0.6
Brightness	3.9 ± 0.6
Contrast	4.0 ± 0.4
Screen Size	4.2 ± 0.6
Glare and Reflection	4.4 ± 0.6
Lag or Delay Screen	4.5 ± 0.5

### C. General User Considerations of the Hand Held Unit

Transducer Size	3.7 ± 0.9
Ease of Use	3.5 ± 0.9
Examination Time	4.3 ± 0.7

Figure 3. The results of comparing various image and imaging unit features of the HHU C60 to ATL clinical units HDI 3000 and UltraMark 4.

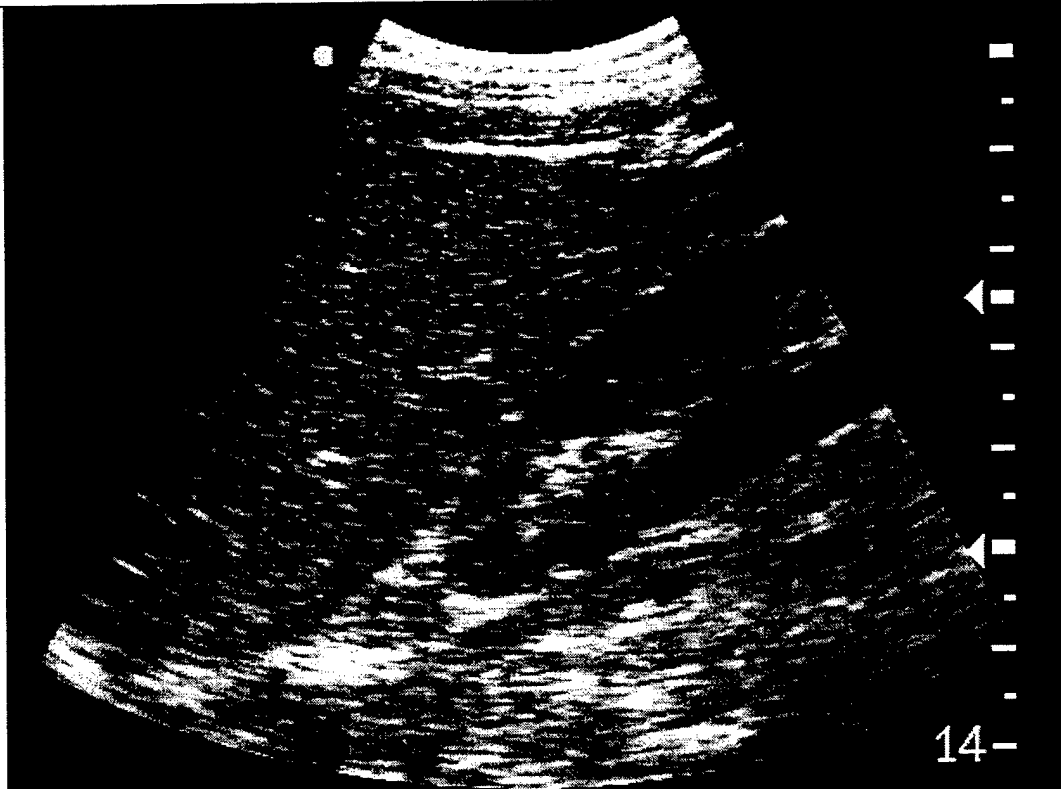


Figure 4A. Image of normal liver acquired with the HHU C60. The probe is located at the top of image.

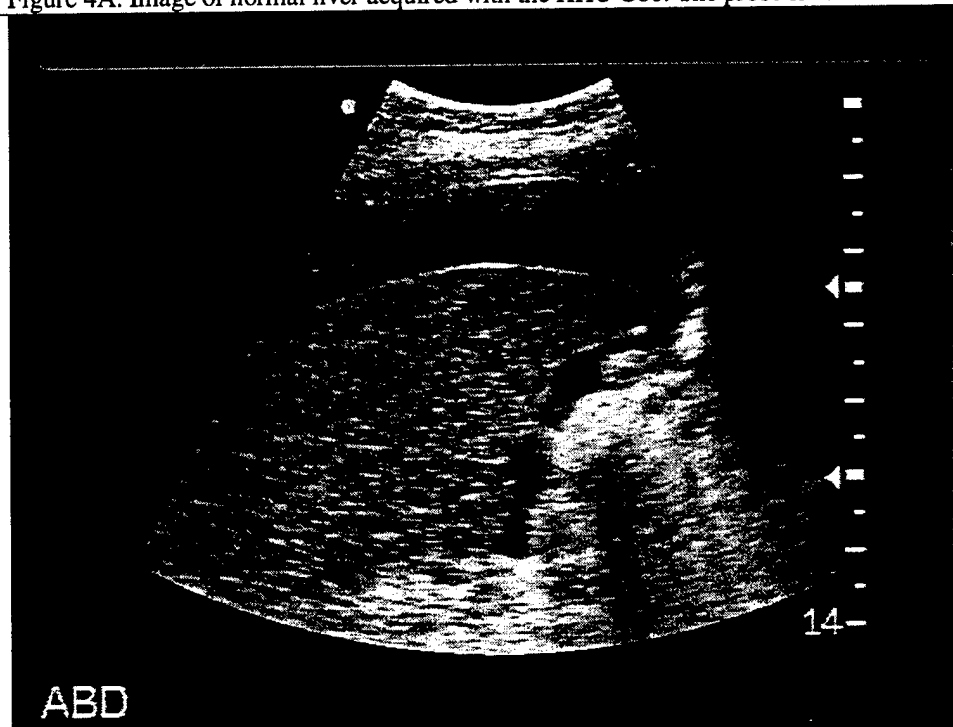


Figure 4B. Image of the liver of the peritoneal dialysis patient with fluid (dark region) surrounding the liver.

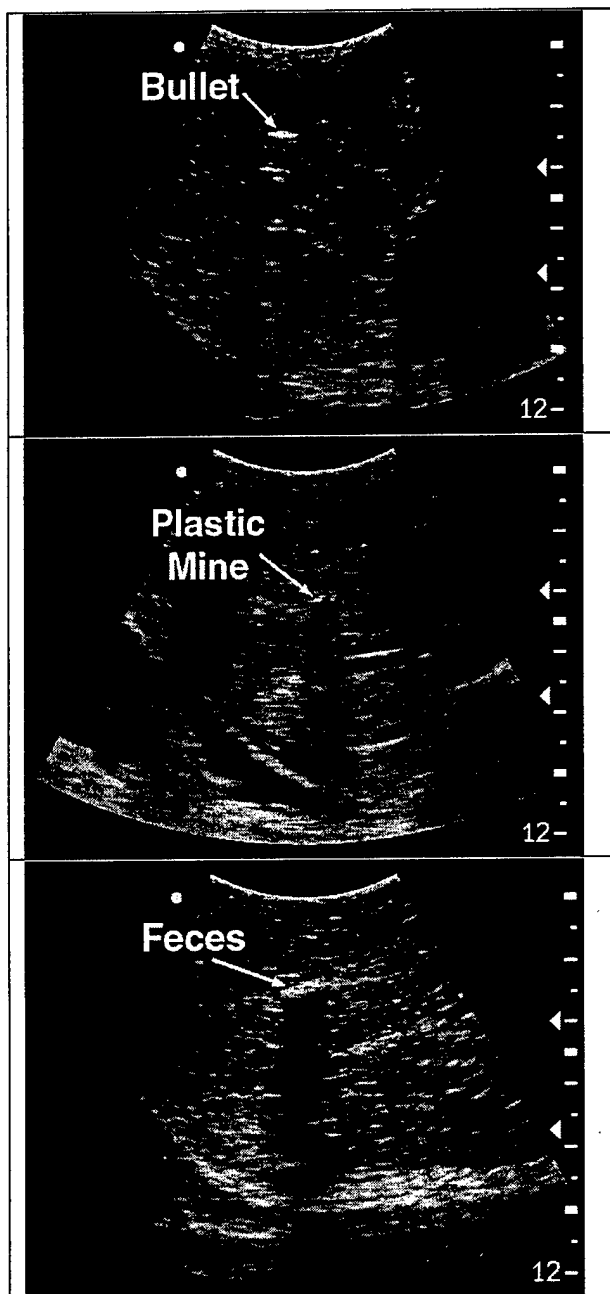


Figure 5. Images of foreign bodies within in vitro swine leg. Transducer position is at the top of the image. The reverberation echoes sometimes referred, as comet tails are characteristic of bullets or other metal objects. The plastic mine appears as bright surface when the transducer is aligned fairly perpendicular to it with a dark shadow behind it due to attenuation of the ultrasound by it. The feces similarly have a bright surface, thought to be due to reflection of air in them. A dark shadowing occurs behind them due the high attenuation. Other highly contaminated materials (e.g. dirt or wood) have similar characteristics.

**Table 1- Light Intensities Measured**

Where - Conditions (Sensor Orientation)	Light Intensity ( $\mu$ watts)
<b>Outside -Sunny Day</b>	
Sunny Location ( Up, Down)	$4-6 \times 10^4$ , $7-8 \times 10^3$
Shady Location ( Up, Down)	$2-3 \times 10^3$ , $1-2 \times 10^3$
<b>Outside -Cloudy Day (Up, Down)</b>	$1-2 \times 10^4$ , $5-8 \times 10^3$
<b>Mash Unit -Cloudy Day (Up)</b>	
Triage Section	$1-1.5 \times 10^4$
Operating Room	$2-3 \times 10^3$
PLX Corridor	0.1-0.3
<b>University -Normal Light (Up)</b>	
Laboratory	$1-3 \times 10^3$
Radiology US Scanning Room	10-100
Radiology Image Reading Room	10- 50

**Table II. Telemedicine comparisons.**

<b>A. Comparison of Subjective Clinical Image Quality of Non-Transmitted Images Versus Transmitted Images (Mean<math>\pm</math>STD)</b>				
Category Number	Non - Transmitted	Transmitted	Non- Transmitted	Transmitted
	HHU-C60	HHU-C60	UltraMark 4	UltraMark 4
1	$4.6 \pm 0.6$	$4.4 \pm 0.5$	$4.8 \pm 0.4$	$4.5 \pm 0.6$
2	$4.7 \pm 0.5$	$4.5 \pm 0.7$	$4.7 \pm 0.5$	$4.7 \pm 0.5$
3	$4.8 \pm 0.5$	$4.8 \pm 0.5$	$4.8 \pm 0.4$	$4.8 \pm 0.4$
4	$4.4 \pm 0.7$	$4.0 \pm 0.5$	$4.7 \pm 0.5$	$4.2 \pm 0.4$
5	$4.7 \pm 0.6$	$4.4 \pm 0.5$	$4.8 \pm 0.4$	$4.7 \pm 0.5$
6	$4.6 \pm 0.6$	$4.3 \pm 0.5$	$4.8 \pm 0.4$	$4.7 \pm 0.5$
7	$4.6 \pm 0.6$	$4.6 \pm 0.5$	$4.7 \pm 0.5$	$4.6 \pm 0.6$
<b>Total</b>	<b><math>4.6 \pm 0.6</math></b>	<b><math>4.4 \pm 0.6</math></b>	<b><math>4.8 \pm 0.4</math></b>	<b><math>4.6 \pm 0.5</math></b>
<b>B. The Value of Telemedicine Features: Comparison Between the Moderate - Expert Ultrasonographer to the Novice - Minimal Trained</b>				
	Moderate.- Expert		Novice- Minimal	
Displaying the Image of Probe and Patient	$2.6 \pm 0.9$		$4.8 \pm 0.5$	
A Graphic Overlay on the Image	$3.7 \pm 0.6$		$4.2 \pm 0.8$	
Audio Channel	$5.0 \pm 0.0$		$5.0 \pm 0.0$	



# Application of the Advanced Communications Technology Satellite to Teleradiology and Real-Time Compressed Ultrasound Video Telemedicine

Brent K. Stewart, Stephen J. Carter, Jay N. Cook, Brian S. Abbe, Deborah Pinck, and Alan H. Rowberg

The authors have investigated the application of the NASA Advanced Communications Technology Satellite (ACTS) to teleradiology and telemedicine using the Jet Propulsion Laboratory (JPL)-developed ACTS Mobile Terminal (AMT) uplink. In this experiment, bidirectional 128, 256, and 384 kbps satellite links were established between the ACTS/AMT, the ACTS in geosynchronous orbit, and the downlink terrestrial terminal at JPL. A terrestrial Integrated Digital Services Network (ISDN) link was established from JPL to the University of Washington Department of Radiology to complete the bidirectional connection. Ultrasound video imagery was compressed in real-time using video codecs adhering to the International Telecommunication Union—Telecommunication Standardization Sector (ITU-T) Recommendation H.261. A 16 kbps in-band audio channel was used throughout. A five-point Likert scale was used to evaluate the quality of the compressed ultrasound imagery at the three transmission bandwidths (128, 256, and 384 kbps). The central question involved determination of the bandwidth requirements to provide sufficient spatial and contrast resolution for the remote visualization of fine- and low-contrast objects. The 384 kbps bandwidth resulted in only slight tiling artifact and fuzziness owing to the quantizer step size; however, these motion artifacts were rapidly resolved in time at this bandwidth. These experiments have demonstrated that real-time compressed ultrasound video imagery can be transmitted over multiple ISDN line bandwidth links with sufficient temporal, contrast, and spatial resolution for clinical diagnosis of multiple disease and pathology states to provide subspecialty consultation and education at a distance.

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**KEY WORDS:** image compression, medical images, satellite, telemedicine, teleradiology, ultrasonography, video compression.

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**T**HE ADVANCED Communications Technology Satellite (ACTS) was successfully launched in September 1993 by the space shuttle Discovery (STS-51). The satellite is presently deployed and operating (Fig 1). The ACTS is in geosynchronous orbit about 19,000 miles above the equator at 100°W longitude—just west of the Galapagos Islands (Fig 2).

The stated goal of the ACTS satellite program is to bring together US industry, government, and academia to test and prove pioneering concepts and technologies that advance on-demand, flexible communication services to strengthen the US economy in the 21st century. ACTS technologies will provide a much higher rate of communications between users—20 times that offered by conventional satellites, greater networking flexibility, and on-demand digital services. Many technical details of the ACTS (eg, the multibeam antenna, broadband processor, microwave switch matrix and control algorithms, and spot beam coverage) have been described in an earlier publication of ours.<sup>2</sup>

Servicing remote regions with state-of-the-art medical diagnostic techniques often is difficult, if not impossible, largely because of the absence of sophisticated telecommunication infrastructure and technical expertise in these areas. If clinical images or video streams were digitized and accurately transmitted from remote areas to urban, teaching medical centers, this could significantly improve medical care to rural and remote populations. Herein we present an investigation of the application of the ACTS to teleradiology and telemedicine using the Jet Propulsion Laboratory (JPL)-developed ACTS Mobile Terminal (AMT) uplink.

**The Ka-band.** The flexible capability of the ACTS satellite with on-demand usage, steerable spot beam, wide bandwidth, and on-board digital switching should allow both ease of use and greatly reduced costs. The sizes of the sending and receiving units also are significantly reduced because of the Ka-band frequencies used (uplink allocation 27.5-30.0 GHz, downlink allocation 17.7-20.2 GHz, Fig 3).

The Ka-band (2.5-GHz bandwidth) is being explored in view of the inevitable congestion of the limited bandwidth available at the L-band, and the

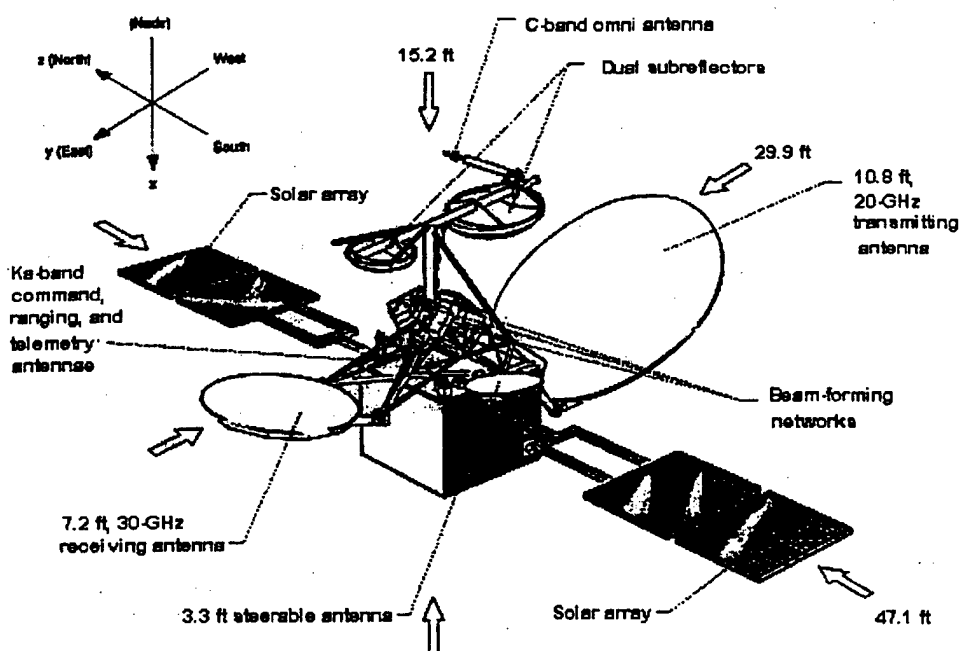


Fig 1. The Advanced Communications Technology Satellite (ACTS) deployed flight configuration. Reprinted with permission.<sup>1</sup>

existing congested allocations at the C- and Ku-bands (0.5-GHz bandwidth each, Fig 3). Moreover, the Ka-band has the potential for supporting user equipment that is significantly smaller and simpler. Therefore, the Ka-band is a good candidate in the pursuit of the high capacities, service diversities, and user convenience sought by current and future satellite users (eg, the Teledesic<sup>3</sup> and Iridium<sup>4</sup> proposals). However, operation in the Ka-band poses significant challenges. Key among these challenges are immature technology, lossy RF components, significant rain attenuation (Fig 3), and large Doppler shifts for mobile applications.

This experiment exploits these capabilities further, using a reduced-size Ka-band antenna to allow portability (mobile van) to rural and remote areas, and the steerable beam of the ACTS satellite (Figs 1 and 2). The AMT mobile van (Fig 4) developed by the JPL uses a 23-cm-diameter antenna that tracks the satellite while the vehicle is moving.

#### ACTS MOBILE TERMINAL

The baseline modulation format of the AMT developed by the JPL is differential phase-shift keying. At its top end, the modem handles up to 384 kbps and is capable of demonstrating compressed video (15 fps) on the uplink. Fade control is

implemented through data rate change at the mobile terminal and uplink power control at the fixed link evaluation terminal (LET).

The AMT is a proof-of-concept experiment designed to overcome the challenges of Ka-band mobile operation and the validation of several key technologies. Two major technical challenges were (1) to maintain the satellite link in a demanding propagation environment (rain fade, Doppler compensation, and antenna pointing algorithms), and (2) the development of enabling Ka-band technologies (eg, low-cost, small-size antenna utilizing Ka-band monolithic microwave integrated circuit components [MMIC] and packaging).

Detailed information regarding the AMT data acquisition system (DAS), Ka-band RF electronics, and maintaining the mobile satellite link can be found in a previous communication of ours.<sup>2</sup>

**AMT antenna.** Two antennae have been developed for the AMT (Fig 5): a passive elliptical reflector antenna and an active phased-array antenna consisting of a multilayered microstrip, an EM-coupled slot, and a dipole MMIC. Both antennae have extremely compact form factors to enable mobile operation. The elliptical reflector antenna is 10-cm high with a 23-cm diameter. The dimensions of the MMIC are 16 cm (L)  $\times$  13 cm (W)  $\times$  2 cm (H).

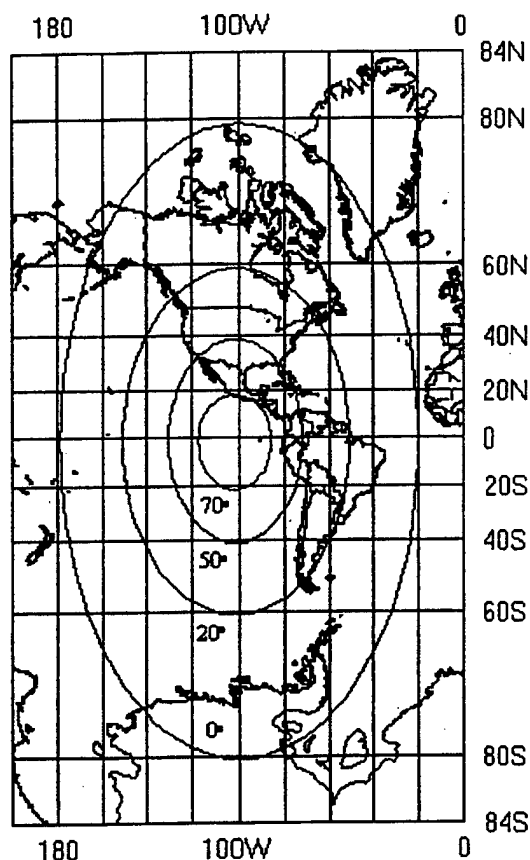


Fig 2. Steerable antenna coverage as a function of the AMT antenna elevation angle.

The 30-GHz MMIC was developed by Texas Instruments. The effective isotropic radiated power (EIRP) is 18.8 dBW for a  $4 \times 4$  array of aperture-coupled microstrip patch radiating elements. This array is fully modular in the sense that multiples of the  $4 \times 4$  units can be placed side-by-side to create larger arrays.

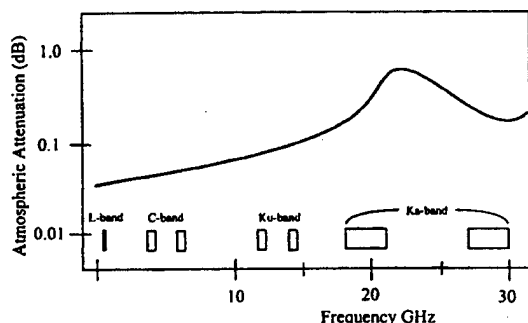


Fig 3. Satellite frequency band allocations and atmospheric attenuation as a function of frequency.

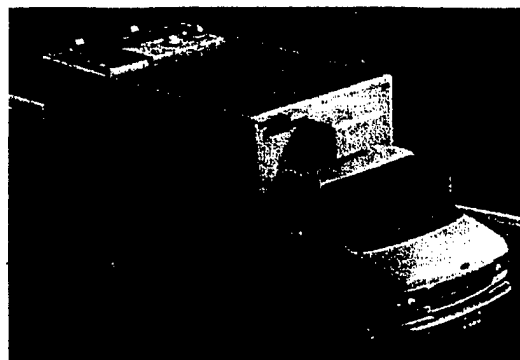


Fig 4. ACTS mobile terminal van. The Ka-band antenna is mounted on the left-rear corner of the roof. Reprinted with permission.<sup>1</sup>

The design specification for each of the elements is 5-dB gain, and the subarray transmitting power is 1.5 W. The 20-GHz downlink antenna also is an MMIC array.

The antenna controller tracks the satellite as the AMT vehicle is in motion. Tracking the satellite requires only azimuthal steering, because the antenna elevation coverage is wide enough to accommodate typical vehicle pitch and roll variations within any single geographic region of operation restricted to paved roads. The antenna controller steers the antenna azimuth angle in response to an inertial vehicle yaw-rate sensor and an estimate of antenna pointing error obtained by "mechanical dithering" of the antenna. The antenna is smoothly rocked (dithered) side-to-side, through a small angle, while the signal strength of the pilot tone received through the antenna is monitored.

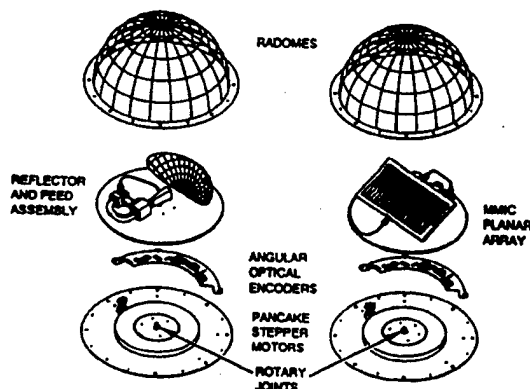


Fig 5. ACTS mobile terminal reflector (left) and active array antennae (right). Reprinted with permission.<sup>1</sup>

### ACTS/AMT EXPERIMENTS

The experiment involved the transmission of digital medical images (computed tomography [CT], magnetic resonance [MR], ultrasonography, computed radiography, and digitized radiographs—including a mammogram) between the field-deployed ACTS/AMT and the Department of Radiology at the University of Washington (UW) in Seattle. This task was accomplished by locating the AMT mobile terminal experiment van in various locations throughout Washington state, Idaho, Montana, and Hawaii. A generic configuration of the test is given in Fig 6.

Data transmission was bidirectional. Digital medical image data files were uplinked to the ACTS and immediately transmitted by the ACTS, thus acting in a "bent pipe" configuration. Medical images were transmitted from the AMT back to the fixed station (consisting of AMT equipment and the high burst rate-link evaluation terminal [HBR-LET]) at the JPL in Pasadena, California. These images were then routed via the Internet or Integrated Digital Services Network (ISDN) from the JPL to the UW Medical Center in Seattle. Once the images arrived in the UW Radiology Department, they were stored on a PC computer disk, were available for softcopy review, and also were printed using a high-quality laser film printer.

The ACTS/AMT experiment involved three phases: (1) initial field testing at 128 kbps, (2) extended field testing of a new high-gain antenna at 384 kbps, and (3) field testing of the high-gain antenna in Hawaii.

**Images and compression.** Several categories of static images were transmitted across the ACTS/AMT satellite link: CT, MR, computed radiographs, and digitized projection radiography films.

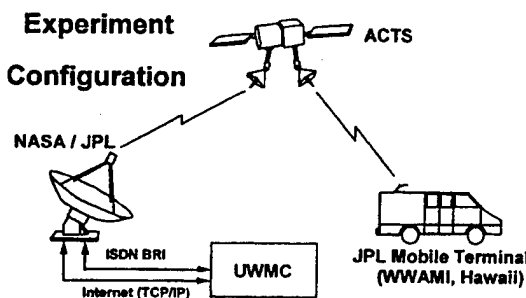


Fig 6. Generic ACTS/AMT "bent pipe" configuration for the University of Washington experiments. WWAMI, Washington, Wyoming, Alaska, Montana, and Idaho.

The smaller image sets (CT and MR) were losslessly compressed using a modified Lempel-Ziv-Welch (LZW) algorithm<sup>5</sup> before transmission, providing an approximate 2.5:1 compression ratio. The JPEG algorithm<sup>6</sup> was used for lossy compression of the larger image sets. The lossy JPEG quality factor was set to provide a 10:1 compression ratio for the larger radiographs so that the compression artifacts were minimal and visually imperceptible. However, the main goal of the experiment was the evaluation of transmitted real-time ultrasound compressed video imagery.

The compression of a video signal digitized to CCIR-601 specifications (approximately 160 Mbps) to a bandwidth capable of being transmitted over satellite connections or low-bandwidth terrestrial links (56 kbps to 1.5 Mbps) requires compressing the signal by approximately 3000:1 to 100:1, respectively. Digitized video data, even after compression at ratios of roughly 400:1 (384 kbps), can be decompressed with close-to-analog VHS videotape quality. There are many means for a video coder-decoder (codec) to achieve these high degrees of compression: (1) reducing the effective luminance and chrominance sampling structure matrix dimensions, (2) reducing the frame rate, (3) a hybrid of interframe prediction to utilize temporal redundancy and transform coding of the remaining signal to reduce spatial redundancy, and (4) various combinations of these three. For the ACTS/AMT experiment, the International Telecommunication Union—Telecommunication Standardization Sector (ITU-T) Recommendation H.320 suite of videoconferencing standards<sup>7</sup> were used, specifically the H.261 Codec for Audiovisual Services at  $p \times 64$  kbit/s,<sup>8</sup> intended for use at video bit rates between approximately 40 kbps and 2 Mbps. A 16-kbps in-band audio channel was used throughout. Both video and audio communications were bidirectional.

Images transmitted over the satellite link were evaluated for artifacts through subjective visual comparison with the originals. The original and transmitted images also were compared using quantitative image processing measurements (eg, normalized mean square error [NMSE] and peak signal to noise ratio [PSNR]). The effect of image and video compression was analyzed by examining the dropout rate versus the bit error rate. In the case of video compression analysis of the H.261 algorithm, the video image quality has been subjectively critiqued

and videotapes of the compressed video transmitted by satellite have been digitized and are being analyzed.

*Initial field testing.* The initial testing was to begin using the Seattle-Portland Fixed Hopping Beam<sup>2</sup>; however, the HBR antenna for the AMT was moved from the NASA Lewis Research Center (LeRC) in Cleveland, Ohio, to the JPL in Pasadena, California. This move meant that both the AMT and the JPL HBR would be using East polarity hopping beams, which is not allowed in the bent-pipe configuration. Therefore, the steerable antenna was used to cover transmissions from the AMT in the Puget Sound basin area, including the UW School of Medicine (Seattle, WA), Madigan Army Medical Center (south of Tacoma, WA), Advanced Technology Laboratories (Bothell, WA), and an ultrasound clinic on Whidbey Island (near Columbia Beach, WA).

The purposes of these experiments were to test the basic functionality of the ACTS/AMT equipment and to perform teleradiology image file transfers (Fig 7) and the more challenging transmission of real-time ultrasound video at 128 kbps between an NEC VisualLinks TC5000 video codec in the AMT and a PictureTel 3000 video codec in the UW Department of Radiology (Fig 8).

*Extended field testing.* The UW School of Medicine (UWSOM), established in 1946, is the only medical school directly serving the five states of Washington, Wyoming, Alaska, Montana, and Idaho (WWAMI). The UWSOM operates a decentralized program of medical education via a network of teaching affiliates throughout the WWAMI region. The WWAMI area comprises approximately 30% of the US landmass (spread over three time zones), but less than 3% of the US population.

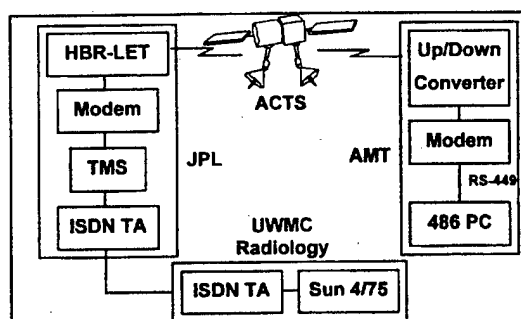


Fig 7. Initial field testing configuration for image file transfer. TA, terminal adapter.

This region is noted for its rugged terrain and diverse climactic conditions, which vary from mild temperatures along the Pacific Coast to extremes of heat and cold in portions of Alaska and on the Great Plains of eastern Montana. The nation's highest mountain chains (the Rocky Mountains, the Cascade Mountain Range, and the Alaska and Brooks Ranges) form natural subregions. As such, UWSOM-WWAMI provides an ideal testbed for rural and remote teleradiology and telemedicine.

Field trials in the WWAMI area were conducted in various types of weather and terrain to test the rain fade compensation and propagation error correction functions of the AMT. In addition, during the extended field testing, real-time compressed video telemedicine links were established (Fig 8) at 128, 256, and 384 kbps using the NEC VisualLinks TC5000 H.261 codecs at both the AMT and UW Department of Radiology ends. In addition, a link-up of the AMT with a medical mobile MR scanner trailer was effected at the Covington Medical Clinic (Kent, WA) for the teleradiology transmission over the ACTS of MR images (Fig 9) from an MR scanner in a mobile trailer.

The UW has been awarded a telemedicine grant from the Office of Rural Health at the Department of Health and Human Services. The purpose of this grant is to provide expert consultation to rural primary care physicians. As part of this grant, desktop PCs were outfitted with video compression boards that operate using the H.320 standard.<sup>7</sup> Four of these systems have been deployed in the following rural sites: Colville, WA; Petersburg, AK; Ronan, MT; and Driggs, ID. An additional four systems have been deployed in the emergency departments of the following Seattle sites: UW Medical Center, Harborview Medical Center (Seattle's level 1 trauma center), Children's Hospital Medical Center, and the Roosevelt Outpatient Center.

It was possible to dial-up any of these telemedicine PCs using the ISDN lines from Pasadena and display the remote video from the AMT on these systems (Fig 8). This demonstrates the utility of mobile remote consultation for emergency triage and disaster relief, and the value of the ubiquity of the H.320 standard to telemedicine.

A simulated MASH environment was arranged at Madigan Army Medical Center. A dozen soldiers were imaged with an ATL HDI-3000 ultrasound machine in a MASH triage tent at Fort Lewis, WA.

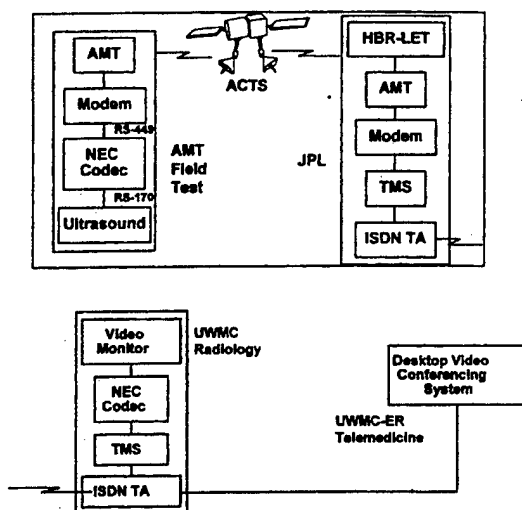


Fig 8. Extended field testing configuration for compressed ultrasound video and teleconferencing.

Video lines were run from that tent to the AMT and the compressed video images viewed at the UW Department of Radiology in real-time. A 384-kbps data rate was used throughout the simulation. From the 12 presumed-normal Special Forces volunteers arose one liver lesion and one gallstone.

**Hawaii field testing.** The Hawaii portion of the ACTS/AMT experiments demonstrated: mobile at-sea transmission with the Navy at Pearl Harbor, relay transmission between a ground station in Micronesia and the ACTS/AMT at Tripler Army Medical Center, and disaster simulation with PacSpace and the Hawaii Civil Defense. Again, the static and real-time video imagery was downlinked from the ACTS to the JPL and transmitted to the UW Radiology Department as described above.

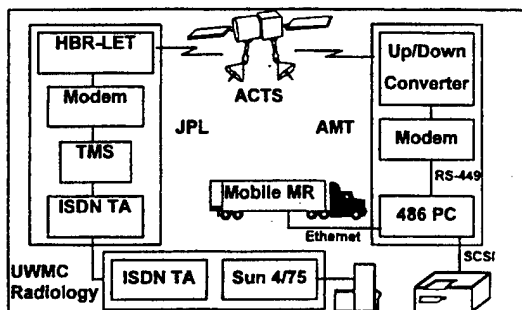


Fig 9. Initial field testing configuration with external modalities, ie, a mobile MR trailer.

## METHODS AND RESULTS

**Teleradiology transmission rates.** To transmit static image data files over the ACTS/AMT link, an independent segment of the Internet was implemented between a Xyplex router in the AMT and an equivalent router at the UW. The TCP/IP (Transport Control Protocol/Internet Protocol) File Transfer Protocol (FTP) was used to transmit files between two 486 PCs utilizing Microsoft Windows 3.1 and connected to the routers through a 10BaseT Ethernet connection. The observed effective data transfer rate was 12,800 (1,440) bits per second (bps) and 23,800 (370) bps when the AMT transmission rate was operated at 128 and 256 kbps, respectively.

These low utilization rates (9.8% and 9.1%, respectively) can be attributed to the relatively long time it takes for data to travel to and from the satellite in geosynchronous orbit and the TCP acknowledgment policy used. The ACTS is in geosynchronous orbit about 19,000 miles above the equator at 100°W longitude. The roundtrip from the AMT to the JPL takes approximately one-half second (0.58 seconds). This is contrasted by the terrestrial telecommunications round trip from Pasadena to Seattle of approximately one-thirtieth of a second.

The TCP/IP sliding window acknowledgement protocol policy<sup>9</sup> for in-order data being accepted by a receiving TCP node has two options concerning the timing of an acknowledgment: (1) when data is accepted, immediately transmit an empty (no-data) segment containing current acknowledgment information, and (2) when data is accepted, record the need for acknowledgment, but wait for an out-bound segment with data on which to piggyback the acknowledgment. Because the transmission of image data for this link was unidirectional FTP transfers, the former TCP/IP acknowledged protocol policy was used, causing low utilization primarily from the large next packet transmission delay, in large part due to the one-half second geosynchronous orbit round trip.

**Compressed ultrasound video evaluation.** Through one of the author's (B.K.S.) previous experiments with compressed ultrasound video transmission,<sup>10</sup> it was determined that the visual quality of real-time compressed ultrasound video is highly dependent on the transmission rate selected for bandwidths below 1.5 Mbps. Thus, a primary objective of the ACTS/AMT experiments was to gather data on the diagnostic quality of the com-

pressed video stream versus transmission data rate (the compression rate is approximately inversely proportional to the transmission rate).

The goal of this radiologist preference testing is to determine the level of compression at which diagnostic signs are no longer interpretable. For each live case, radiologists and sonography technologists were asked to complete the form shown in Fig 10. This form consists of fields for the type of examination (eg, abdominal ultrasonography) and the data rate for compressed video transmission. A five-point Likert scale<sup>11,12</sup> was used to gauge the viewer's impression of the diagnostic quality: 1—no useful diagnostic information, 2—little useful information, 3—some useful information, 4—moderate diagnostic quality, and 5—good diagnostic quality. The results of the questionnaire were analyzed using a combination of descriptive and summation statistics (Table 1).

Based on the analysis of the sampling provided in Table 1, it can be seen that at 128 kbps, the real-time compressed ultrasound video image quality for the abdomen, kidney, and liver provided, at best, some grossly useful information. At 256 kbps, the image quality for the abdomen, carotid artery,

fetal survey, and thyroid provided fair to moderate diagnostic quality, with a wide spread among viewers. At 384 kbps, all imaging categories provided predominantly good image quality with a fairly small degree of variance among the viewers.

All compressed ultrasound video sessions transmitted at the various bandwidths (40 hours' worth) were videotaped using high-quality S-VHS recorders and media at the transmit and receive ends. S-VHS produces a minimal degradation in image quality compared with video compression effects. This will allow for further evaluation of compressed ultrasound video image quality as a function of bandwidth with a larger number of reviewers.

### DISCUSSION

Overall, the transmission of static images and compressed ultrasound video operated better than anticipated. Although there were no problems establishing a TCP/IP network using the ACTS, the TCP acknowledgment protocol used caused problems due to the long propagation delays of the ACTS geosynchronous orbit. As the video codecs impose a compression stream delay of about one-half second per side, the extra-geosynchronous delay

#### Clinician Subjective Preference Testing

##### NASA/JPL - AMT - UW Radiology

Please rate your clinical impression using the 1-5 scale: 5 = best, 1 = worst.

5	4	3	2	1
Good Diagnostic Quality.	Moderate Diagnostic Quality	Fair Diagnostic Quality	Some Grossly Useful Information	No Useful Diagnostic Information
e.g., organ parenchymal detail visualized	e.g., can R/O significant hydronephrosis or abdominal fluid	e.g., only gross pathology	e.g., some organ margins visualized	

Your Name: _____				
Date: _____		Time: _____		
Data Rate: _____				
Type of Examination (e.g., abdominal US): _____				
Live: _____		Tape: _____		
5	4	3	2	1
Comments: _____				

Fig 10. Likert scoring forms used to assess diagnostic quality for various anatomic regions at different transmission bandwidths.

**Table 1. Ultrasound Radiologist and Ultrasonographer Likert Scoring for Compressed Ultrasound Video at Receiving End for Various Anatomic Locations**

Anatomy	Data Rate (kbps)	Likert Score Mean (SD)
Abdomen	128	1 (0)
	256	3.13 (0.85)
	384	4.45 (0.71)
Carotid artery	256	3.7 (n/a)
	384	4.70 (0.36)
Fetal	256	3.80 (0.28)
Kidney	128	2 (0)
	256	3.50 (0.71)
	384	5.0 (0)
Liver	128	2 (0)
	384	4.67 (0.58)
Pancreas	384	5 (0)
Spleen	384	5 (0)
Thyroid	256	3.10 (1.98)
	384	4.03 (0.74)

did not in itself cause a large impediment to the video component of the telemedicine consultations. However, the delay time did cause some problems when two people started talking within one or two seconds of each other. In that case, just as with the Ethernet carrier-sense multiple access with collision detection (CSMA/CD) protocol, a verbal collision detection algorithm must be employed to produce a meaningful two-way dialog. This meant that upon collision, both parties backed off for a few seconds and then began speaking again. However, this could lead to further collisions. The preferred method was a token ring network-type protocol with expression of the verbal token "over" relinquishing control of the audio link.

We see this study as a platform for the application and implementation of real-time compressed ultrasound video for clinical application within the UW Academic Medical Center. As part of our work under an ultrasound telemedicine contract with the Defense Advanced Research Projects Agency (DARPA), we have developed an infrastructure to transmit real-time compressed ultrasound video over local area networks consisting of FDDI and switched 10BaseT Ethernet. This is being used to connect the radiology departments at the UW Medical Center, the Harborview Medical Center

(Seattle's level 1 trauma center), and the Roosevelt Outpatient Clinic, somewhat compensating for limited staffing of the ultrasound sections as well as facilitating physician-to-physician consultation.

We also view this study as a platform for the investigation of providing remote real-time ultrasound imaging at the point-of-need. If highly portable ultrasound units with video codecs and telecommunication links were available to health care providers in the nursing home, or to nurses in the obstetrics ward, or even to paramedics in an ambulance (we have demonstrated that the AMT can transmit images and video while in motion)—and they were all trained to acquire the images for review by an ultrasound expert via telemedicine—the ultrasound examination could be taken to the patient. This not only would allow examinations in situations such as remote and emergency scenarios, but also would keep the patient from being transported to the examination site (hospital or clinic), eliminating both transportation costs and inconvenience to the patient. This ultrasound instrument portability also might allow patients to spend more time at home and less time in care facilities such as nursing homes. The use of highly portable ultrasound devices with telemedicine capabilities has the potential for increased diagnostic ultrasound utilization and reduced health care costs, while also providing an extended range of quality health care.

The authors are currently participating with Advanced Technology Laboratories in a funded DARPA TRP (Technology Reinvestment Program) to develop a lightweight (less than 3 lb), fully functional (including color Doppler and power Doppler capabilities) ultrasound device. This is a joint collaboration between the UW Department of Radiology, the UW Applied Physics Laboratory and Advanced Technology Laboratories (Bothell, WA), Harris Semiconductor (Palm Bay, FL), and VLSI Technology, Inc (San Jose, CA). The goal of the telemedicine component of this ARPA TRP is the design, analysis, and testing of wavelet video compression algorithms specifically tailored for diagnostic ultrasound imaging over civilian and military communication infrastructures.

## REFERENCES

1. NASA: Space Communications Program Outreach and Public Relations Department
2. Stewart BK, Carter SJ, Rowberg AH: Application of the advanced communications technology satellite for teleradiology and telemedicine. *Proc SPIE* 2435:210-219, 1995
3. Sturza MA: The Teledesic satellite system, in Hoffman MI (ed): 1994 IEEE National Telesystems Conference, 1994, pp 123-126
4. Leopold RJ, Miller A: The Iridium communications system. *IEEE MTT-S Int Microwave Symp Digest* 2:575-578, 1993
5. Welch TA: A technique for high-performance data compression. *Computer* 17:8-19, 1984



6. Wallace GK: The JPEG still picture compression standard. *Comm. ACM* 34:30-44, 1991
7. Dallal I, Mustillo P: CCITT audiographics standards, in Ed: Phillips D, Desrochers P (eds): *Proceedings of the Multimedia Communications '93*, 1993, pp 213-215
8. Liou ML: Overview of the  $p \times 64$  k bits/s video coding standard. *Comm ACM* 34:59-63, 1991
9. Stallings W: *Handbook of Computer Communication Standards*, vol 3, The TCP/IP Protocol Suite. Carmel, IN, Howard W. Sams & Co, 1990
10. Gold RH, Kangaroo H, Grant EG, et al: Teleconferencing for cost-effective sharing of radiology educational resources: Potential and technical development. *AJR* 160:1309-1311, 1993
11. Meetz HK, Bebeau MJ, Thoma SJ: The validity and reliability of a clinical performance rating scale. *J Dent Educ* 52:290-297, 1988
12. Merrill JM, Camacho Z, Laux LF, et al: Uncertainties and ambiguities: Measuring how medical students cope. *Med Educ* 28:316-322, 1994

# A 3-D Wavelet-Based Codec for Lossy Compression of Pre-Scan-Converted Ultrasound Video

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## ABSTRACT

We present a wavelet-based video codec based on a 3-D  $(x,y,t)$  wavelet transformer, a uniform quantizer/dequantizer and an arithmetic encoder/decoder. The wavelet transformer uses biorthogonal (9,7) Antonini wavelets in the two spatial dimensions and Haar wavelets in the time dimension. Multiple levels of decomposition are supported. The codec has been applied to pre-scan-converted ( $r$ -theta or polar coordinate) ultrasound image data and does not produce the type of blocking artifacts that occur in MPEG-compressed video. The PSNR (peak signal to noise ratio) at a given compression rate increases with the number of levels of decomposition: for our data at 50:1 compression, the PSNR increases from 18.4 dB at one level to 24.0 dB at four levels of decomposition. Our 3-D wavelet-based video codec provides the high compression rates required to transmit diagnostic ultrasound video over existing low bandwidth links without introducing the blocking artifacts which have been demonstrated to diminish clinical utility.

**Keywords:** Wavelets, video compression, video codec, diagnostic ultrasound

## 1. INTRODUCTION

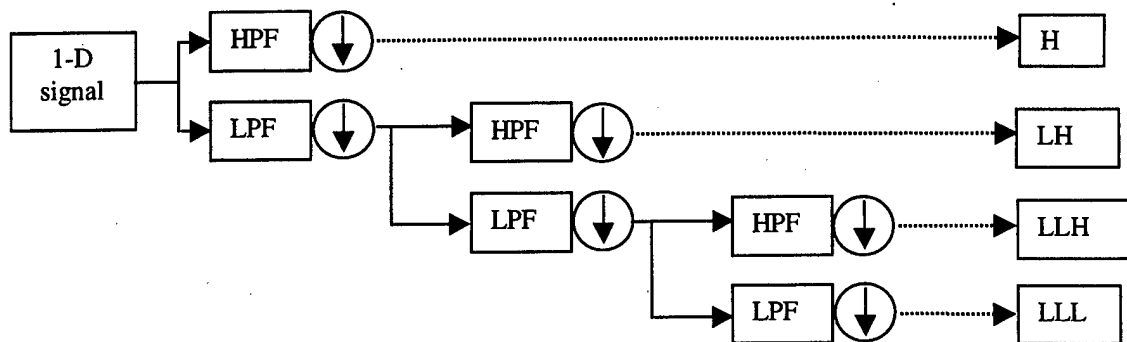
Currently deployed communication links (Internet, intranets, telephone lines) cannot support real-time delivery of full-bandwidth diagnostic ultrasound video. Real-time links can only be achieved with lossy video compression techniques, which reduce the video bandwidth but also degrade the video content. The MPEG compression standard relies on block-based processing which, at severe compression ratios, introduces blocking artifacts. We have developed an alternative compression technique using interframe wavelets as well as intraframe wavelets in order to achieve similar compression rates without these blocking artifacts.

Previous work<sup>1</sup> investigated lossy compression of diagnostic ultrasound video using 2-D wavelet compression on each frame of a video sequence. This intraframe or motion wavelet technique did not exploit any interframe correlation. The wavelet codec presented here utilizes both inter- and intra-frame correlation simultaneously. We demonstrate much higher compression rates at similar PSNRs on diagnostic ultrasound video than those reported for motion wavelet techniques.

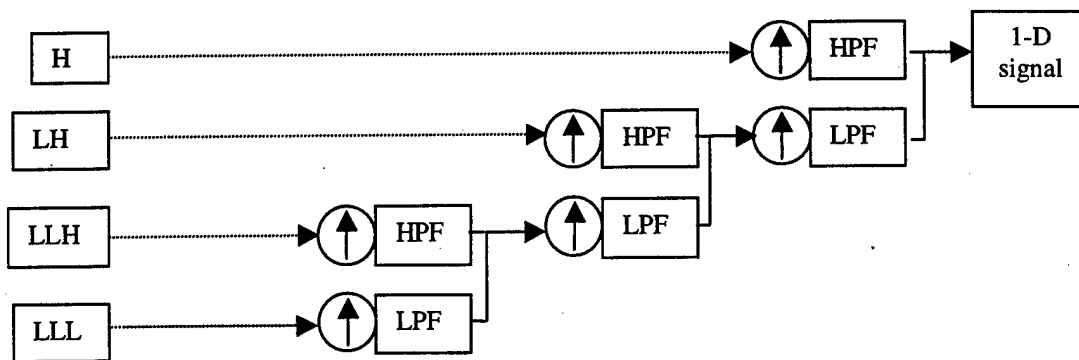
## 2. 3-D WAVELET TRANSFORMER

Hierarchical video streams result when the information is decomposed in a multiresolution analysis<sup>2</sup>. Here, the information is analyzed into one or more levels. At each level, the information is filtered into details (high frequency information) and an approximation (low frequency information). An example<sup>3</sup> for a three-level decomposition of a 1-D signal is shown in figure 1. The corresponding reconstruction is shown in figure 2. The approximation and details are together referred to as subbands.

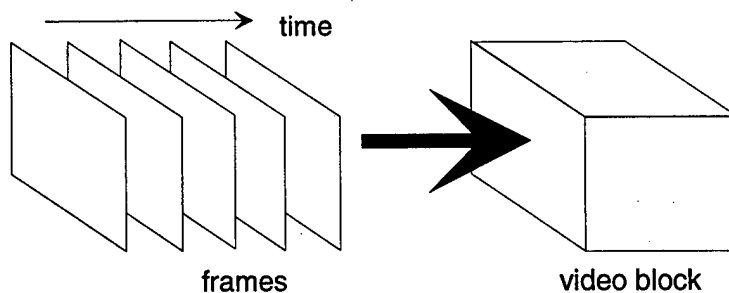
The corresponding structure for a 3-D signal is much more complicated. First, a sequence of video frames are grouped together as shown in figure 3 to form a  $(x,y,t)$  block. Similar organizations have been reported earlier<sup>4,5</sup>. A single level of decomposition is shown in figure 4, and the corresponding single level reconstruction shown in figure 5. In  $N$ -D, each subband is an  $N$ -D structure, and each level of the multiresolution analysis generates  $2^N$  subbands. For a 3-D signal, each level generates 8 subbands.



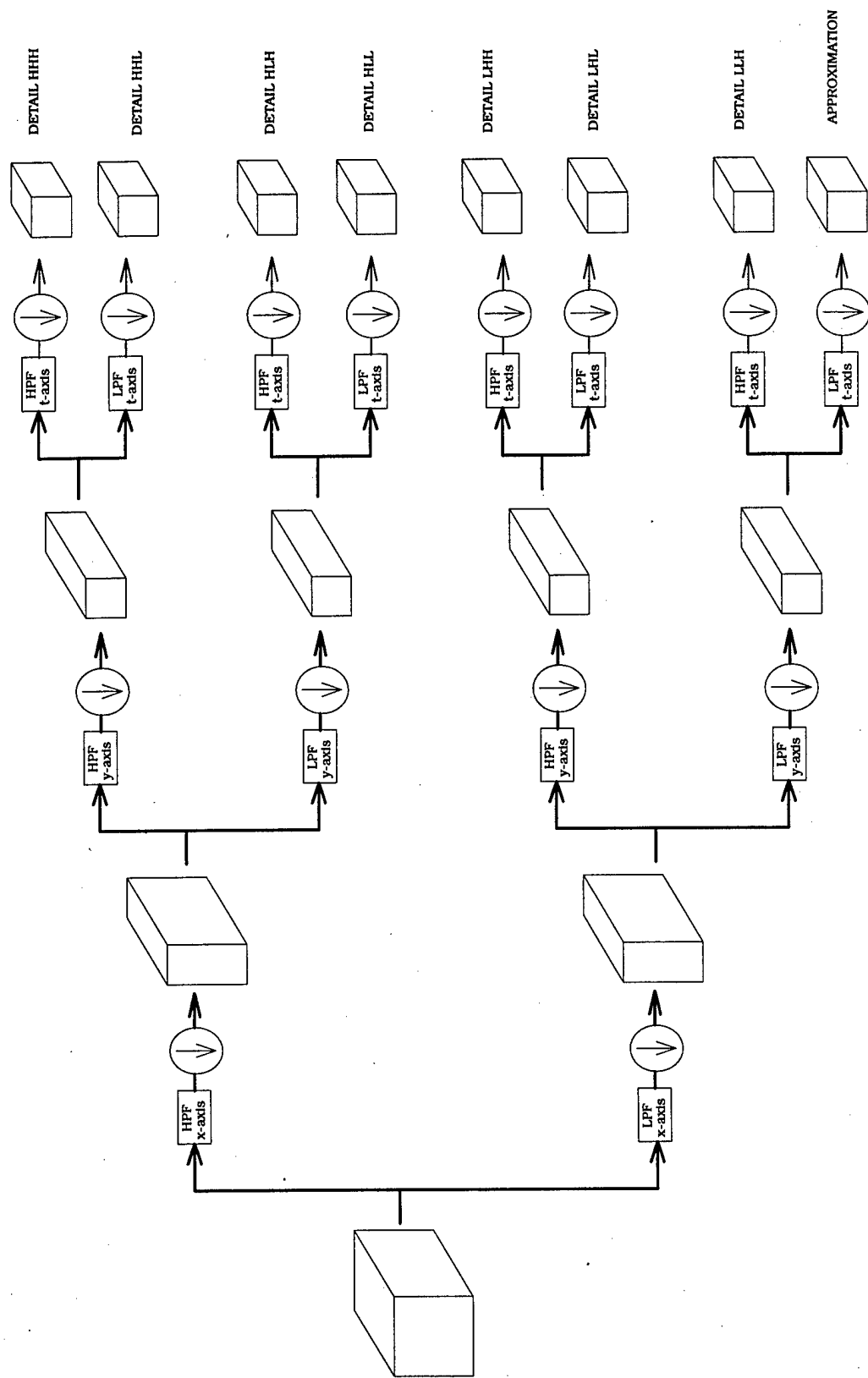
**Figure 1.** Three level decomposition of a 1-D signal. The output components are H (level 1 details), LH (level 2 details), LLH (level 3 details) and LLL (level 3 approximation.) The down-arrows represent downsampling. HPF and LPF represent high-pass and low-pass decomposition filters, respectively.



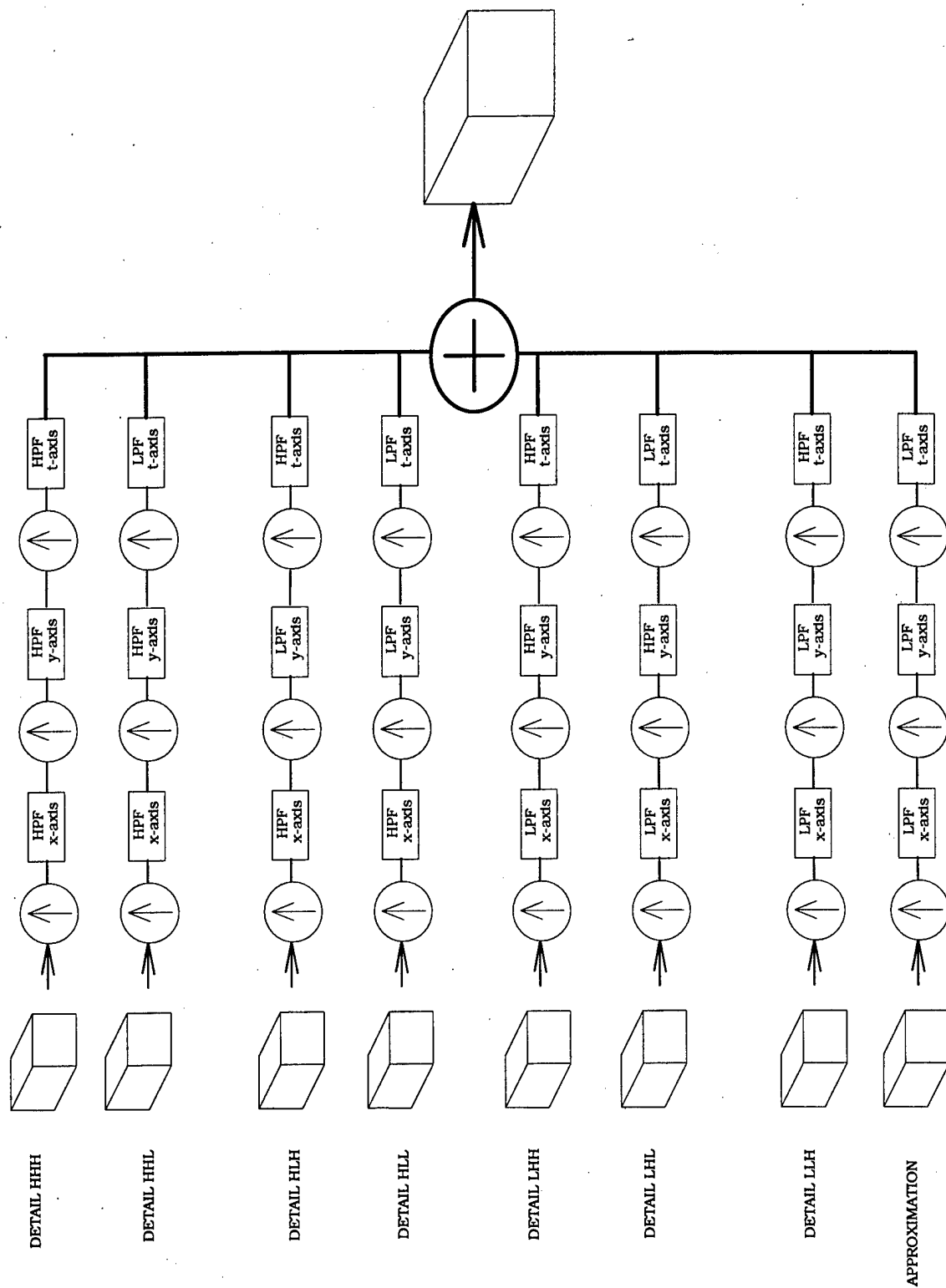
**Figure 2.** Three level reconstruction of a 1-D signal. The possible input components are LLL (level 3 approximation), LLH (level 3 details), LH (level 2 details) and H (level 1 details). The up-arrows represent upsampling. HPF and LPF represent high-pass and low-pass reconstruction filters, respectively.



**Figure 3.** Assembly of a sequence of video frames into a 3-D video block structure.



**Figure 4.** A single level of a 3-D wavelet decomposition. The 3-D data is shown schematically as a block which is square in  $x$  and  $y$  dimensions and has depth along the time dimension: the individual frames along time are not shown explicitly. The down-arrows represent downsampling by 2.



**Figure 5.** A single level of a 3-D wavelet reconstruction. The up-arrows represent upsampling by 2 along a single axis, effected by interleaving zeros with the data. (The three upsamplers in each path operate on the  $x$ ,  $y$  and  $t$  axes respectively.)

The biorthogonal (9,7) Antonini wavelets<sup>7</sup> have generally been found to be adequate for image compression, so we tested our code with these wavelets along either spatial dimension. In the time dimension, previous studies<sup>4,5</sup> have suggested using a simple Haar wavelet.

### 3. CODEC REALIZATION

We implemented the 3-D codec by interfacing the 3-D discrete wavelet transform (DWT) onto the quantizer/encoder classes developed at Dartmouth. The Dartmouth wavelet construction kit has three basic C++ classes, as shown in figure 6: a 2-D transformer, quantizer and coder. Two types of quantizers are provided in the distribution: a uniform monolayer quantizer, and an embedded multilayer quantizer. The coder is an arithmetic encoder with adaptive histogram support. Our 3-D codec implementation substitutes a 3-D DWT for their 2-D DWT, and uses the monolayer quantizer.

Similarly, our scheme for implementing the decoder required adding 3-D DWT support to their 2-D decoder, as shown in figure 7.

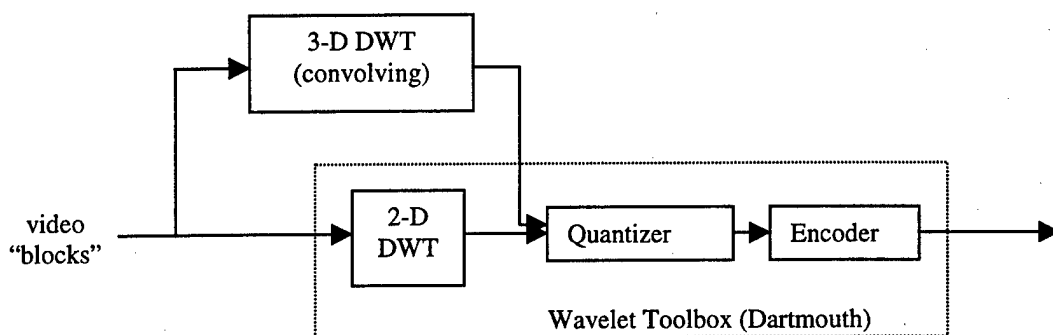


Figure 6. Block Diagram for Adding 3-D Support to the Dartmouth Package.

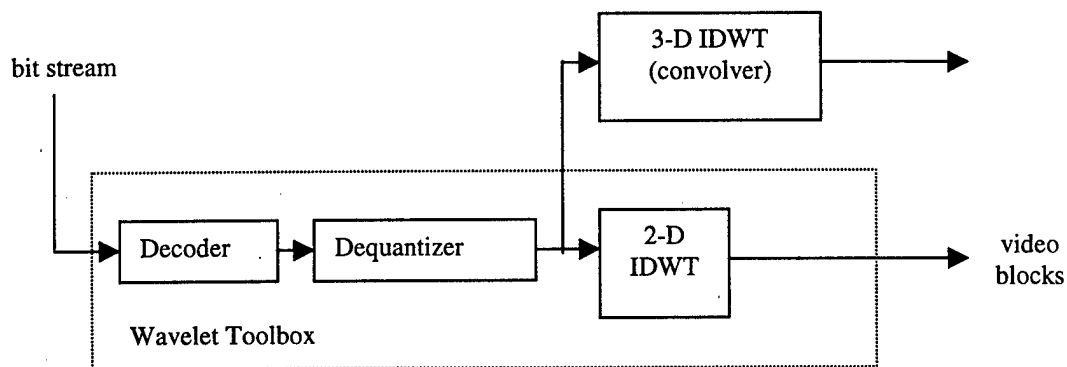


Figure 7. Block Diagram for Adding 3-D Support to the Dartmouth Package.

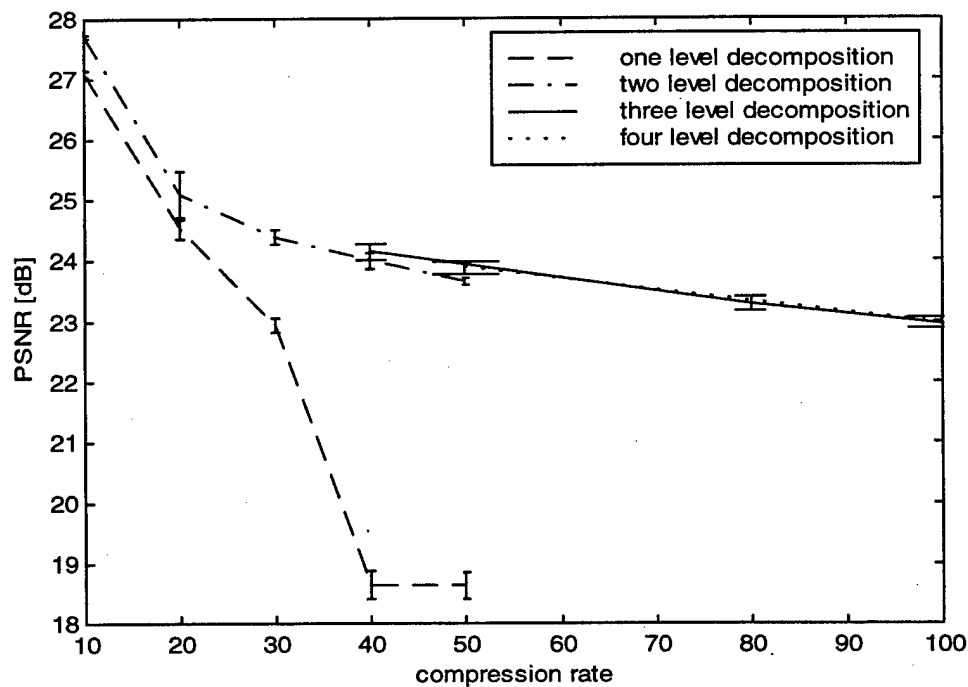
#### 4. APPLICATION TO PRE-SCAN-CONVERTED ULTRASOUND

In collaboration with ATL Ultrasound (Bothell, WA)<sup>8</sup>, we acquired 69 frames of pre-scan-converted data. Ultrasound imaging scanners typically interrogate the subject over a sample space that is rectangular in polar coordinates. Scan conversion transforms the echo data into the more familiar sectorized image. This sectorized image is then combined with some annotation and delivered to the scanner screen and also sometimes to a video output jack. Considerable regions of the frame involve information that is irrelevant (the background), changing slowly (the annotation) or not changing at all (the intensity bar). These components of the frame have a much lower information density than the sectorized image. Computational resources should not be spent compressing this kind of information, as it can be transmitted much more efficiently by alternate means. More importantly, the sectorized image itself is not an efficient shape for compression as compared to the pre-scan converted polar data<sup>9</sup>. We therefore applied our video codec to the raw polar data prior to scan-conversion.

Each pre-scan-converted image consisted of 128 rays of 512 8-bit estimates (= 64k bytes). The data was acquired with an ATL HDI-3000 using a C7-4 curved linear array. Total depth was ~10.5 cm. The images were a sweep through a healthy adult kidney, and represented typical radiology data. The data were acquired with a 15-fps frame rate. Frames 0 – 31 were grouped into one 128 x 512 x 32 byte 3-D video block; frames 32 – 63 into a second, thus yielding a total of 4 seconds of video data. Each 3-D video block was processed by the wavelet codec with varying levels of decomposition and compression, as shown in table 1. The codec computes several figures of merit, one of which is the peak signal to noise ratio (PSNR), defined by

$$PSNR = 10 \log_{10} \left( \frac{255^2}{MSE} \right)$$

where *MSE* is the mean square error, computed in the bit allocator during compression, and represents the mean error per pixel between the original data and the reconstructed data given the target level of wavelet coefficient quantization. The *PSNR* provides a measure of signal-to-reconstruction-error for a full-scale (8-bit) signal. The PSNR versus compression rates for the four levels of decomposition used are shown in figure 8.



**Figure 8.** PSNR versus compression rate for the pre-scan-converted data. Compression rates range from 10:1 to 100:1. One, two, three and four levels of decomposition were used. Error bars represent the range of PSNR values over two samples.

levels	target compression	actual compression	PSNR	resulting target bandwidth
1	10:1	10.06:1	27.09 dB	419 Kbps
	20:1	21.23:1	24.52 dB	210 Kbps
	30:1	32.04:1	22.92 dB	140 Kbps
	40:1	43.85:1	18.64 dB	105 Kbps
	50:1	50.60:1	18.41 dB	83.9 Kbps
2	10:1	10.06:1	27.70 dB	see above
	20:1	20.21:1	25.09 dB	
	30:1	30.60:1	24.39 dB	
	40:1	40.53:1	24.01 dB	
	50:1	51.06:1	23.66 dB	
3	40:1	40.17:1	24.15 dB	105 Kbps
	80:1	81.34:1	23.28 dB	52.4 Kbps
	120:1	121.8:1	22.60 dB	35.0 Kbps
	160:1	163.1:1	22.27 dB	27.8 Kbps
	200:1	203.4:1	22.04 dB	21.0 Kbps
4	50:1	50.19:1	23.88 dB	83.9 Kbps
	100:1	100.6:1	22.95 dB	41.9 Kbps
	150:1	151.3:1	22.43 dB	28.0 Kbps
	200:1	203.0:1	22.10 dB	21.0 Kbps
	250:1	255.3:1	21.81 dB	16.8 Kbps
	300:1	306.1:1	21.70 dB	14.0 Kbps
	350:1	358.3:1	21.60 dB	12.0 Kbps
	400:1	412.3:1	21.54 dB	10.5 Kbps

**Table 1.** Decomposition levels and compression rate combinations for processing pre-scan-converted data. Two 32-frame video blocks were processed and their mean reported. The actual compression rate used a value called total rate reported by the bit allocator, and does not include the size of any header information written to disk. The PSNR was reported by the bit allocator. The bandwidth uses the target compression rate and assumes delivery of the 64 frames over 4 seconds.

(It should be noted that these values of PSNR are raw values obtained by analysis on the pre-scan converted video. System values, which model the entire ultrasound instrument as a single system and analyze the compression obtained on the instrument video output, is likely to be poorer.)

Subjective visual comparison clearly shows that increasing the number of levels of decomposition improves video quality at the same compression rate. With only one decomposition level, the LLL subband commandeers the bit budget leaving no room for any of the detail subbands. At higher decomposition levels, the LLL subband is much smaller, leaving more room in the bit budget for one or more detail subbands (at any of the levels), thus providing video images with sharper resolution.

Two additional metrics were used to compare each frame in the compressed video against the original video: a correlation coefficient  $\rho^{(i)}$  and the normalized mean squared-error  $NMSE^{(i)}$ . The metrics for the  $i^{th}$  frame were computed using

$$\rho^{(i)} = \frac{\frac{1}{N} \sum_{j,k} f_{j,k}^{(i)} g_{j,k}^{(i)}}{\sqrt{MSS(f^{(i)})} \sqrt{MSS(g^{(i)})}}$$



and

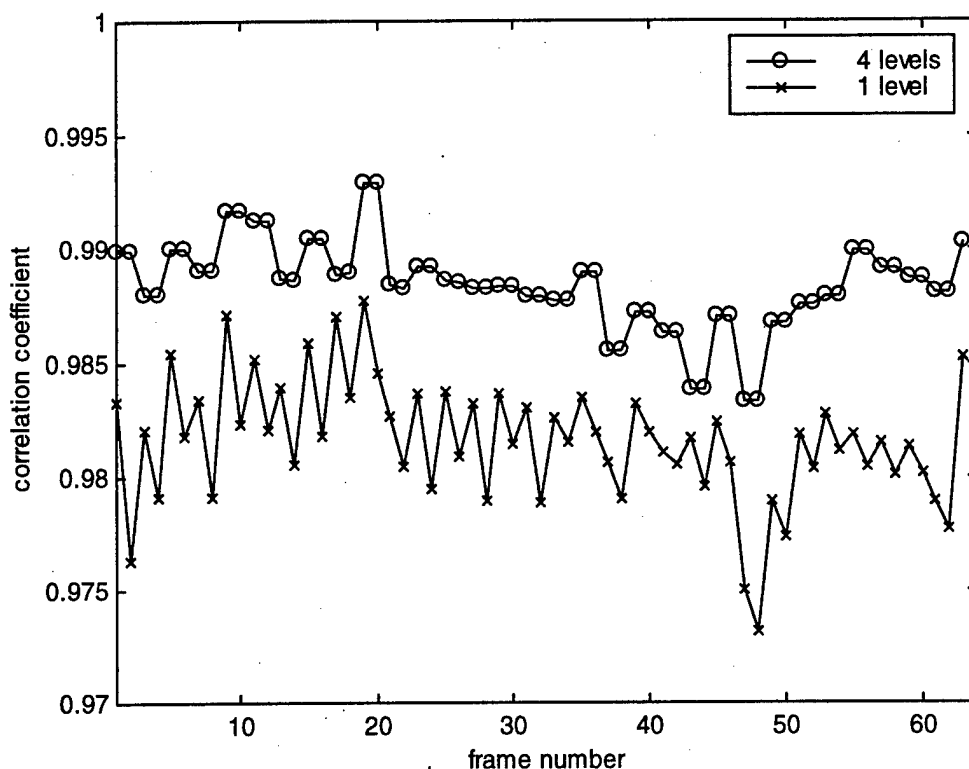
$$NMSE^{(i)} = \frac{MSE(f^{(i)}, g^{(i)})}{\sqrt{MSS(f^{(i)})} \sqrt{MSS(g^{(i)})}},$$

where the mean squared error  $MSE$  is  $MSE(f^{(i)}, g^{(i)}) = \frac{1}{N} \sum_{j,k} |f_{j,k}^{(i)} - g_{j,k}^{(i)}|^2$ , the mean squared signal  $MSS$  is

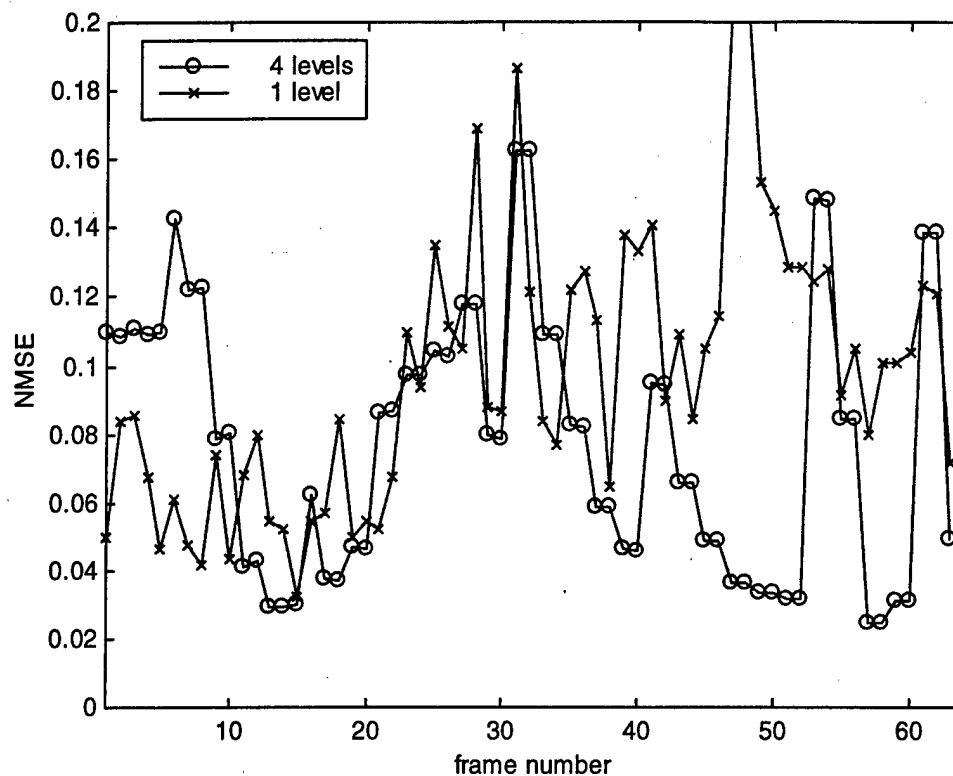
$$MSS(f^{(i)}) = \frac{1}{N} \sum_{j,k} |f_{j,k}^{(i)}|^2, \quad f_{j,k}^{(i)}$$
 is the  $(j,k)^{th}$  pixel of the  $i^{th}$  input frame and  $g_{j,k}^{(i)}$  is the  $(j,k)^{th}$  pixel of the  $i^{th}$  lossy

compressed-decompressed frame. Each frame is assumed to have  $N$  total pixels. The raw values  $\rho^{(i)}$  and  $NMSE^{(i)}$  are plotted against frame number in figures 9 and 10 respectively.

Figure 9 confirms that 4 level decomposition maintains a higher fidelity (here in terms of the correlation coefficient) than 1 level decomposition. Figure 10 is less definitive, but throughout most of the video the 4 level decomposition has a lower NMSE.



**Figure 9.** Correlation coefficient per frame between the original video and the wavelet compressed-decompressed video. Shown are results for 1 and 4 levels of decomposition. 50:1 compression.



**Figure 10.** Normalized mean squared error per frame between the original video and the wavelet compressed-decompressed video. Shown are results for 1 and 4 levels of decomposition. 50:1 compression.

An interesting visual effect is suggested by the grouping of  $\rho^{(i)}$  values into pairs in figure 9. In moving from 2-D compression (motion wavelet, for example) to 3-D, the codec exploits the high degree of interframe correlation. However, as described above, the approximation (low-pass) information in the time dimension commands a significant portion of the bit budget. This implies that the dominant effect after compression is a low-pass filtering along the time axis. The wavelet along the time-axis is a Haar wavelet, which only spans two frames at a time (at 1 level decomposition.) Consequently, as the target compression rate increases, the codec appears to be replacing groups of  $K$  consecutive frames with their time-averaged mean frame, rather than passing distinctly different frames. (Here,  $K$  varies from about 2 to 4). This effect is already apparent in figure 9 where the correlation is similar for each frame pair group.

The visual effect is that the video acquires a choppy appearance, as if the original input video frame rate had been decreased. In essence, the codec is dropping frames. The individual frames remain sharp, and do not have the blurring associated with MPEG-based block artifacts: after downloading the entire video (or a portion thereof) the user can still step through the video one frame at a time and view sharply resolved images.

The use of a broader wavelet along the time dimension should reduce the choppy appearance, at a cost of image sharpness in each frame.

## 5. SUMMARY AND CONCLUSIONS

We have developed a hierarchical wavelet video codec that uses biorthogonal (9,7) Antonini wavelets in the two spatial dimensions and Haar wavelets in the time dimension. The wavelet transformer was interfaced with a monolayer uniform quantizer and an arithmetic coder from Dartmouth to produce the full codec implementation.

The codec was demonstrated on pre-scan-converted data. Under severe compression, the video contains considerably fewer artifacts than video compressed via MPEG at similar compression rates. The codec accomplishes this by simultaneously trading off spatial and temporal resolution. The object definition in each frame, however, remains quite distinct, even beyond a compression ratio of 200:1. The PSNR at a given compression rate increases with the number of levels of decomposition: for our data at 50:1 compression, the PSNR increases from 18.4 dB at one level to 24.0 dB at four levels of decomposition.

At higher compression levels, the video starts to acquire a choppy appearance, an effect we attribute to the short Haar filter used along the time dimension. Future investigations will use a more extended wavelet in the time dimension to reduce choppiness along the time dimension in the video.

The use of gray-scale pre-scan-converted video enabled us to achieve clinically useful data at bandwidths as low as 50 Kbps. This result indicates that 3-D wavelet compression can provide the high compression rates required to transmit diagnostic ultrasound video over existing low bandwidth links without introducing the blocking artifacts which have been demonstrated to diminish clinical utility.

## 6. ACKNOWLEDGEMENTS

The first author thanks J. Cabral at the University of Washington for insightful discussions.

## 7. REFERENCES

1. Andrew, R., B. Stewart, S. Langer and K. Stegbauer, "Wavelet Compression of Ultrasound Video Streams for Teleradiology", *Proceedings 1998 IEEE International Conference on Information Technology Applications in Biomedicine (ITAB '98)*, May 1998, Washington, D.C.
2. Mallat, S., "A theory for multiresolution signal decomposition: the wavelet representation", *IEEE Trans. Pattern Recog. and Mach. Intell.*, vol. 11 (7), pp 674 - 693, July 1989.
3. Vetterli, M., and J. Kovacevic, "*Wavelets and Subband Coding*", Prentice-Hall, Ltd., 1995.
4. Lewis, A. S., and G. Knowles, "Video compression using 3-D wavelet transforms", *Elec. Letters*, vol. 26, no. 6, pp. 396-398, 15 March 1990.
5. Taubman, D., and A. Zakhor, "Multirate 3-D subband coding of video", *IEEE Trans. on Image Proc.*, vol. 3(5), pp 572-588, September, 1994.
6. Davis, G., has provided the source code (C++) for a "wavelet toolbox" that includes a number of state-of-the-art algorithms for 2-D transforms and embedded quantizers. . Online documentation at URL <http://www.cs.dartmouth.edu/~gdavis/wavelet/wavelet.html>.
7. Antonini, M., M. Barlaud, P. Mathieu, "Image coding using wavelet transforms", *IEEE Trans. Image Proc.*, vol. 1(2), pp 205-220, April 1992.
8. ATL web URL is <http://www.atl.com>.
9. Cabral, J.E., Jr., D. T. Linker and Y. Kim, "Compression for pre-scan-converted ultrasound sequences," *Proc SPIE* 3335, pp. 378-387, 1998.

# Compressed Ultrasound Video Image Quality Evaluation Using a Likert Scale and Kappa Statistical Analysis

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## ABSTRACT

Experiments using NASA's Advanced Communications Technology Satellite were conducted to provide an estimate of the compressed video quality required for preservation of clinically relevant features for the detection of trauma. Bandwidth rates of 128, 256 and 384 kbps were used. A five point Likert scale (1=no useful information and 5=good diagnostic quality) was used for a subjective preference questionnaire to evaluate the quality of the compressed ultrasound imagery at the three compression rates for several anatomical regions of interest. At 384 kbps the Likert scores (mean  $\pm$  SD) were abdomen (4.45  $\pm$  0.71), carotid artery (4.70  $\pm$  0.36), kidney (5.0  $\pm$  0.0), liver (4.67  $\pm$  0.58) and thyroid (4.03  $\pm$  0.74). Due to the volatile nature of the H.320 compressed digital video stream, no statistically significant results can be derived through this methodology.

As the MPEG standard has at its roots many of the same intraframe and motion vector compression algorithms as the H.261 (such as that used in the previous ACTS/AMT experiments), we are using the MPEG compressed video sequences to best gauge what minimum bandwidths are necessary for preservation of clinically relevant features for the detection of trauma. We have been using an MPEG codec board to collect losslessly compressed video clips from high quality S-VHS tapes and through direct digitization of S-video. Due to the large number of videoclips and questions to be presented to the radiologists and for ease of application, we have developed a web browser interface for this video visual perception study. Due to the large numbers of observations required to reach statistical significance in most ROC studies, Kappa statistical analysis is used to analyze the degree of agreement between observers and between viewing assessment. If the degree of agreement amongst readers is high, then there is a possibility that the ratings (i.e., average Likert score at each bandwidth) do in fact reflect the dimension they are purported to reflect (video quality versus bandwidth). It is then possible to make intelligent choice of bandwidth for streaming compressed video and compressed videoclips.

**Keywords:** Image Compression, Image Quality, Kappa Statistics, Likert Scale, Medical Images, Telemedicine, Teleradiology, Ultrasound, Video Compression

## 1. INTRODUCTION

The Advanced Communications Technology Satellite (ACTS) was successfully launched in September 1993 by the space shuttle Discovery (STS-51). The satellite, presently deployed and operating, is in geosynchronous orbit about 19,000 miles above the equator at 100 degrees W longitude - almost directly above the Galapagos Islands.

The ACTS is an experimental test-bed designed to demonstrate pioneering concepts and technologies that advance more economical, on-demand communications. It is the precursor to currently proposed Ka-band satellite networks that will blanket the globe, such as the Teledesic network of 840 satellite spanning the globe in low earth orbit (200-mile elevation). Many technical details of the ACTS, e.g., the multibeam antenna, broadband processor, microwave switch matrix and control algorithms and spot beam coverage have been described in an earlier publication by the authors [1].

The ACTS Mobile Terminal (AMT) mobile van (Figure 1) developed by the Jet Propulsion Laboratory (JPL) uses a 23 centimeter diameter antenna which can track the ACTS while the vehicle is moving. During 1995, we participated in a series of experiments (Figure 2) in conjunction with the JPL to test the transmission of compressed real-time ultrasound video using the ACTS AMT [2]. The compressed real-time video/audio stream produced by a ITU-T (International Telecommunication Union - Telecommunication Standardization Sector) H.320 standard video codec (coder-decoder) was transmitted from the AMT to the ACTS and from the ACTS to the fixed ground station (consisting of AMT equipment and the high burst rate-link evaluation terminal) at the Jet Propulsion Laboratory (JPL) in Pasadena, California. The video/audio stream was then routed via Integrated Digital Services Network (ISDN) from JPL to the University of Washington Medical Center (UWMC) in

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Seattle. The real-time compressed video/audio stream was decompressed at the University of Washington using another H.320 standard codec and the resulting analog video/audio stream displayed/played on a 25" video monitor with S-video input.

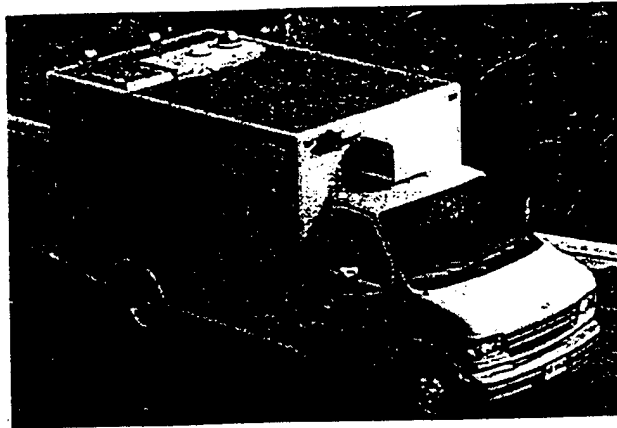


Figure 1. ACTS Mobile Terminal van. The Ka-band antenna is mounted on the left-rear corner of the roof. Reproduced with permission of the Jet Propulsion Laboratory.

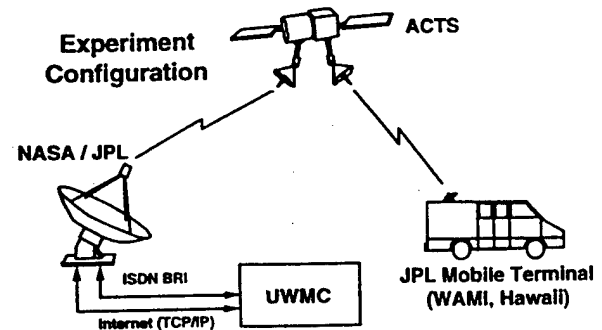


Figure 2. Generic ACTS/AMT "bent pipe" configuration for the University of Washington experiments. WAMI = Washington, Alaska, Montana and Idaho.

## 2. CHARACTERISTICS OF VIDEO SIGNALS

How much data is there in video? The current standard for component color video digitization is CCIR (International Radio Consultative Committee) 601 which prescribes a spatial resolution of 720 samples horizontally and 480 samples vertically. Sampling rates are based on multiples of 3.375 Msamples/second. Sampling rate multiples can vary for the luminance and chrominance signals, usually given by sampling ratios of luminance:chrominance (red channel -  $C_r$ ):chrominance (blue channel -  $C_b$ ); see Figure 3. The green chrominance can be reconstructed from these three signals. The 4:2:0 sampling rate scheme is adequate for most applications where video compression is to be employed. The luminance is sampled at every sample point, but as can be seen in Figure 3,  $C_r$  and  $C_b$  are sampled every other sample point and every other sample line. The undersampling of color can be justified based on extensive studies of the psychophysics of color vision. If 8-bit sampling is used for intensity and chrominance, the data rate to store this real-time digitized video is 20.25 Mbytes/sec or 160 Mbps. This is equal to 1.2 Gbytes/min or 73 Gbytes/hour.

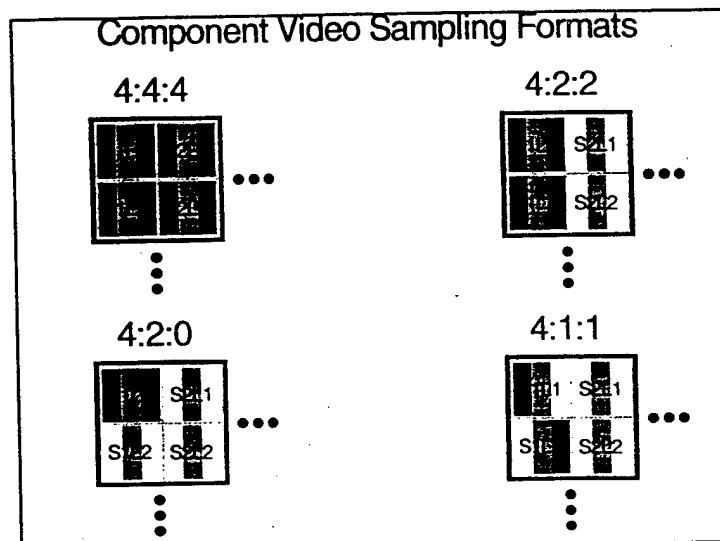


Figure 3. Digital video luminance and chrominance sampling schemes.

How can this digital video stream be compressed? There are many means for a video codec to achieve these large degrees of compression: (1) a hybrid of inter-picture prediction to utilize temporal redundancy and transform coding of the remaining signal to reduce spatial redundancy, (2) reducing the frame rate, (3) reducing the effective luminance and chrominance sampling structure matrix dimensions, and (4) various permutations of these three. Using the 4:2:0 schema already introduces the concept of sub-sampling that can be performed spatially and temporally (periodically dropping adjacent frames). Essentially we want to remove the redundancies and leave only the entropy (non-stationary) signal to be transmitted to the remote location.

There are a number of extant standards for video compression which are extensions of the JPEG intraframe compression standard: Motion-JPEG (no still frame redundancies removed, thus limiting the compression ratio), ITU-T (International Telecommunication Union - Telecommunication Standardization Sector) Recommendations H.261/H.263 and the MPEG-1 and MPEG-2 standards. Video data, even after compression at rates close to 128 kbps can be decompressed with close to analog VHS videotape quality. Sample compression ratios are given in Tables I and II.

Table I. Compression Ratio versus bandwidth. CIF=common intermediate format (352 x 288). QCIF = quarter CIF (176 x 144). BRI = ISDN basic rate interface of 128 kbps).

Bandwidth at 30 fps	CIF Comp. Ratio (wrt CCIR 601)	QCIF Comp. Ratio (wrt CCIR 601)
T-1 (1544 kbps)	27:1 ( 108:1)	7:1 ( 108:1)
3 BRI ( 384 kbps)	105:1 ( 432:1)	26:1 ( 432:1)
2 BRI ( 256 kbps)	158:1 ( 648:1)	40:1 ( 648:1)
1 BRI ( 128 kbps)	316:1 (1296:1)	79:1 (1296:1)

Table II. Compression ratio versus frame rate (at 384 kbps).

Frames per second (fps)	CIF Comp. Ratio (wrt CCIR 601)	QCIF Comp. Ratio (wrt CCIR 601)
3.75	13:1 (432:1)	3.3:1 (432:1)
7.5	26:1 (432:1)	6.6:1 (432:1)
15	53:1 (432:1)	13:1 (432:1)
30	105:1 (432:1)	26:1 (432:1)

For the ACTS/AMT experiment, the International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) Recommendation H.320 suite of videoconferencing standards [3] were used, specifically the H.261 Codec for Audiovisual Services at px64 kbit/s [4], intended for use at video bit rates between approximately 40 kbps and 2 Mbps. A 16 kbps audio channel was used throughout. Both video and audio communications were bi-directional.

### 3. COMPRESSED ULTRASOUND VIDEO EVALUATION

Through one of the author's (BKS) previous experience [5], the clinical utility of real-time compressed ultrasound video depends heavily on the transmission rate selected. Thus, a primary objective of the ACTS/AMT experiments was preliminary data on the diagnostic quality of the compressed video stream versus transmission data rate (the compression rate is approximately inversely proportional to the transmission rate).

The results of this radiologist preference testing will indicate at what level of compression relevant diagnostic signs are no longer interpretable. For each live case over the ACTS, radiologists and sonography technologists were asked to fill out the form shown in Figure 4. This form consists of fields for the type of examination (e.g., abdominal US) and the data rate for compressed video transmission. A five point Likert scale [6,7] was used to gauge the viewers impression of the diagnostic quality: 1 = no useful diagnostic information, 2 = little useful information, 3 = some useful information, 4 = moderate diagnostic quality, and 5 = good diagnostic quality. The results of the questionnaire was analyzed using a combination of descriptive and summation statistics (Table III). An initial analysis is presented in Table 1.

Based on the analysis of the limited sampling given in Table III, it is seen that at 128 kbps, the real-time compressed ultrasound video image quality for the abdomen, kidney and liver provides at best some grossly useful information. At 256

kbps, the image quality for the abdomen, carotid artery, fetal survey and thyroid provided somewhere between fair and moderate diagnostic quality, with a wide spread amongst viewers. At 384 kbps, all imaging categories provided predominately good image quality with a fairly small degree of variance amongst the various viewers.

All compressed ultrasound video sessions transmitted at the various bandwidths (40 hours worth) were videotaped using high-quality S-VHS recorders and media at the transmit and receive ends. S-VHS produces a very minimal degradation in image quality as compared with the video compression effects. This will allow for further evaluation with a largely increased number of reviewers and reviews of the compressed ultrasound video image quality as a function of bandwidth. This should provide more definitive results that can be analyzed statistically for significance.

Clinician Subjective Preference Testing  
NASA/JPL - AMT - University of Washington Radiology

Please rate your clinical impression using the 1-5 scale: 5 = best, 1 = worst.

5 .....	4 .....	3 .....	2 .....	1
<b>Good Diagnostic Quality</b>  e.g., organ parenchymal detail visualized	<b>Moderate Diagnostic Quality</b>  e.g., can R/O significant hydronephrosis or abdominal fluid	<b>Fair Diagnostic Quality</b>  e.g., only gross pathology	<b>Some Grossly Useful Information</b>  e.g., some organ margins visualized	<b>No Useful Diagnostic Information</b>

Your Name: \_\_\_\_\_

Date: \_\_\_\_\_ Time: \_\_\_\_\_

Data Rate: \_\_\_\_\_

Type of Examination (e.g., abdominal US): \_\_\_\_\_

Live: \_\_\_\_\_ Tape: \_\_\_\_\_

Comments: \_\_\_\_\_

Figure 4. Likert scoring forms used to assess diagnostic image quality for various anatomical regions at different transmission bandwidths.

Table III. Ultrasound radiologist and ultrasonographer Likert scoring (Figure 4) for compressed ultrasound video at the receiving end for various anatomical locations.

Anatomy	Data Rate (kbps)	Likert Score Mean (SD)
Abdomen	128	1 (n/a)
	256	3.13 (0.85)
	384	4.45 (0.71)
Carotid Artery	256	3.7 (n/a)
	384	4.70 (0.36)
Fetal	256	3.80 (0.28)
Kidney	128	2 (n/a)
	256	3.50 (0.71)
	384	5.0 (0.0)

Anatomy	Data Rate (kbps)	Likert Score Mean (SD)
Liver	128	2 (n/a)
	384	4.67 (0.58)
Pancreas	384	5 (n/a)
Spleen	384	5 (n/a)
Thyroid	256	3.10 (1.98)
	384	4.03 (0.74)

The major problem we encountered with the ACTS video perception trials were the volatility of the video imagery on both the uncompressed, live scanning end or on the compressed receiving end. While it is possible to store both the uncompressed and compressed video on S-VHS magnetic tape using VCRs, this adds appreciable degradation to the analog stored video. What we would ideally like to do is capture the live scanning ultrasound video as a digitized file on a computer (e.g., and AVI – audio visual interleaved) and compress this file to produce another digital file that can be consistently replayed for various observers in the perception tests. However, the H.320 algorithm has traditionally been packaged in a “turnkey” approach that takes the input video and audio, compresses it, impresses it on a bitpipe where it is decompressed and returned to the analog realm, without the digital video/audio stream being stored on a digital medium. As such it is volatile and not amenable to reproducible testing. Although it is possible to run an evaluation study in real-time in this manner, it is much too time and resource intensive and not flexible enough to user for the large number of observations that are necessary in the pursuit of statistical significance.

As there are many parallels between the H.261 algorithm and MPEG-1 encoding (interframe differencing, the use of 8 x 8 Discrete Cosine Transforms and motion compensation), and the fact that MPEG encoding provides an output file that is readily playable on many computer platforms, it was decided to use MPEG-1 encoded videoclips for further perception testing.

#### 4. MPEG COMPRESSION OF COLLECTED AVI VIDEO CLIPS

We are using the Data Translation (Marlboro, MA) Broadway MPEG video codec to capture direct S-video and S-VHS videotape sequences to computer disk as an AVI file. As mentioned above, it is much more convenient and scientifically valid to directly capture the digital compressed video stream and play these back via PCs with high-resolution monitors to the radiologists.

As the MPEG standard has at its roots many of the same intraframe and motion vector compression algorithms as the H.261 (such as that used in the previous ACTS/AMT experiments [1,2]), we are using the MPEG compressed video sequences (.mpg files) to best gauge what minimum bandwidths are necessary for preservation of clinically relevant features for the detection of trauma. We have been using the MPEG codec board to collect losslessly compressed (.avi file) video clips from high quality S-VHS tapes for imaging exams performed in the clinic. The MPEG files are then created at specified playback bandwidths using the Broadway MPEG-1 hardware video codec GUI interface tools. [Note: currently we are directly digitizing real-time ultrasound video directly to AVI videoclips using a PCMCIA video frame grabbing card in a laptop PC.]

A priori compression ratios were established to provide a given output bit rate (128, 256, 384, 512, 768 and 1544 kbps). These compressed video clips (and an original with no lossy compression - .avi) can then be played back for the observing radiologists who then fill out the appropriate Likert form for the given anatomy/pathology visualized in that videoclip (see the section on Likert Evaluation using Kappa Statistics).

#### 5. VIDEOCLIP FEATURE LIKERT EVALUATION

A five point Likert [6,7] scale is used to gauge the viewer's impression of the diagnostic quality of the MPEG compressed video clips. For each videoclip selected for the study, the readers (board-certified ultrasound radiologists) assess key diagnostic features on a scale from 1-5 (see Table IV). An example of the key feature questions addressed to the readers for the MPEG videoclip of the right upper quadrant (RUQ, liver-kidney boundary = Morison's pouch) presented in Figure 5 are given in Table V.

Table IV. Five point Likert scale ratings.

Likert scale rating	Specified feature diagnostic quality
1	No useful diagnostic information
2	Some grossly useful information
3	Fair diagnostic quality
4	Moderate diagnostic quality
5	Good diagnostic quality



## 6. VIDEOCLIP SELECTION

Of the dozens of number of AVI video clips collected thus far, only six were selected for the initial Likert evaluation. These are video clips of anatomy or pathology best representing the mix that might be found in trauma or emergency situations. Table V lists the selected video clips. Tables V and VII through XI delineate the key features to be extracted from the Likert assessment.



Figure 5. Right Upper Quadrant MPEG compressed ultrasound video clip at 384 kbps playback bandwidth (30 fps).

Table V. Right Upper Quadrant: video compression key feature Likert evaluation questions.

1. Visualization of kidney and liver contours?
2. Fluid visualization (i.e., can R/O significant fluid and blood in Morisons pouch)?
3. Normal respiratory motion?
4. Comparative echogenicity (i.e., liver > kidney)?
5. R/O hydronephrosis?
6. R/O dilated biliary ducts?
7. R/O renal or hepatic fracture?

Table VII. Video clips selected for the initial Likert evaluation study with anatomy.

1. Right Upper Quadrant (RUQ)	kidney, liver, and Morisons pouch	Table V
2. Abdominal Cross Section	pancreas, liver, aorta, inferior vena cava, splenic vein, renal vein, superior mesenteric artery and kidney	Table VII
3. Early Pregnancy	viable fetus, inter-uterine pregnancy (IUP), amniotic fluid, and yolk sac	Table VIII
4. Aorta Cross Section	aorta	Table IX
5. Aorta Longitudinal View	aorta, and superior mesenteric artery	Table X
6. Testicular Trauma	testicle	Table XI

Table VII. Abdominal Cross Section: video compression key feature Likert evaluation questions.

1. Overall anatomic detail
2. Pancreas visualization?
3. Liver visualization (portion included)?
4. Large vessel visualization (e.g., aorta, inferior vena cava (IVC))?
5. Other vessel visualization (e.g., splenic vein, renal vein and superior mesenteric artery (SMA))?
6. R/O dilated ducts?
7. R/O abnormal blood/fluid collection?

Table VIII. Early Pregnancy: video compression key feature Likert evaluation questions.

1. Inter-uterine pregnancy (IUP) identified?
2. Fetal viability visualization (fetal heart motion - FHM)?
3. Ability to estimate approximate fetal age?
4. Amniotic fluid within normal limits?
5. R/O abnormal blood and fluid collection and membrane separation (on this view)?
6. Yolk sac visualized?

Table IX. Aorta Cross Section: video compression key feature Likert evaluation questions.

1. Aorta identified?
2. Aneurysm?
3. Dissection?
4. False lumen visible?
5. R/O abnormal fluid or blood?

Table X. Aorta Longitudinal View: video compression key feature Likert evaluation questions.

1. Aorta visualized?
2. Celiac axis and superior mesenteric artery (SMA) visualization?
3. R/O aneurysm?
4. R/O dissection (on this view)?
5. Vascular pulsations?

Table XI. Testicular Trauma: video compression key feature Likert evaluation questions.

1. Evidence of trauma?
2. Anatomical structure of testicle?
3. Evidence of fluid or blood?
4. Fracture lines or hematoma?

## 7. MPEG BANDWIDTH (COMPRESSION) SELECTION

As was determined in the analysis of previous ACTS/AMT Likert descriptive and summation analysis [2], there is a marked change in the MPEG and H.261 codec video quality going from 256 kbps/second (kbps) bandwidth (158:1 compression ratio) and 384 kbps bandwidth (105:1 compression ratio). Note: all of these MPEG compression ratios are generated at CIF resolution (352x288); see Table I. There is noted a slow progression in improvement from 384 kbps through the T-1 rate (1544 kbps = 27:1 compression ratio). The T-1 bandwidth video looks almost indistinguishable to the original, losslessly compressed AVI video clip, except for very minute and transitory blocking artifacts where the imagery changes discontinuously, as one would expect. As there are six separate videoclips with on the average six questions per videoclip, we have decided for the initial Likert evaluation to use only the 256, 384, and T-1 videoclips, which limits the number of questions for each viewing session to 108 questions.

## 8. WEB INTERFACE

Due to the large number of permutations for the initial Likert evaluation mentioned above, it was decided that collection of paper records would be inconvenient and prone either loss or error. In addition, we sought a means of effortless display and question answering to speed the radiologists through the Likert evaluation as quickly as possible. It is very hard to get physicians to participate otherwise. Thus, we have developed a web browser interface using Microsoft (Redmond, WA) Explorer 3.0 and Front Page 97.

The web interface is shown in Figures 6 and 7. After entering their first and last names and reading a text section describing the Likert evaluation (Fig 6), the web interface allows the physician to play the videoclip by simply pressing a play button. The videoclip and playback controls are imbedded into the webpage using Active X controls. Simple videoclip movie controls (play, stop and a slider for temporal positioning within the videoclip) are available for the physician to interrogate the clip at their leisure (Fig 7). The Likert evaluation questions relevant to that specific video clip are displayed beside the videoclip and the rating from 1-5 is entered from the keyboard for each question (Fig 7). Range limits on the input of the Likert score prevent many mistaken entries. After answering each question, the physician can then summon the next videoclip using hyperlinks. Physicians are allowed to replay and reanswer any videoclip until they close out the evaluation session, whereupon, the results are written out to a disk file. The viewing session results resident on the disk file are then available for analysis using Kappa statistics that are described in the next section.

**Introduction**

This page will take you through a series of 3 images and videoclips of varying anatomy and contrast resolution. Please learn with your keyboard the controls that access the 3 images. Clicking on the triangle button will initiate the videoclip. Although some of the videoclips may present in grayscale, some or both other displaying anatomy, please only comment on the videoclips as they appear. Please do not comment on the contrast resolution of the videoclips. This is not a testing, contrast resolution and of the individual questions. We encourage an average number from 1 to 5 for the 30 questions regarding clarity.

Please read the 30 questions and answers and click on the 30 questions. You will find the 30 questions. As you find you may want to go back and forth through the 30 questions. Please do not be in a hurry to go through answering the questions. We encourage you to take your time. When you have completed all 30 questions and are satisfied with your responses, click on the 30 questions and click on the 30 questions. When you have completed all 30 questions, click on the 30 questions and click on the 30 questions.

1	2	3	4	5
Good Diagnostic Quality	Moderate Diagnostic Quality	Fair Diagnostic Quality	Some Clarity, Usable Information	No Usable Diagnostic Information
e.g. organ structure clearly visible	e.g. organ structure somewhat visible or not clearly visible	e.g. only gross pathology	e.g. some organ margins visualized	

Last Name:

First Name:

Case #:

Figure 6. Front page of the Likert evaluation web browser: introductory notes and identification.

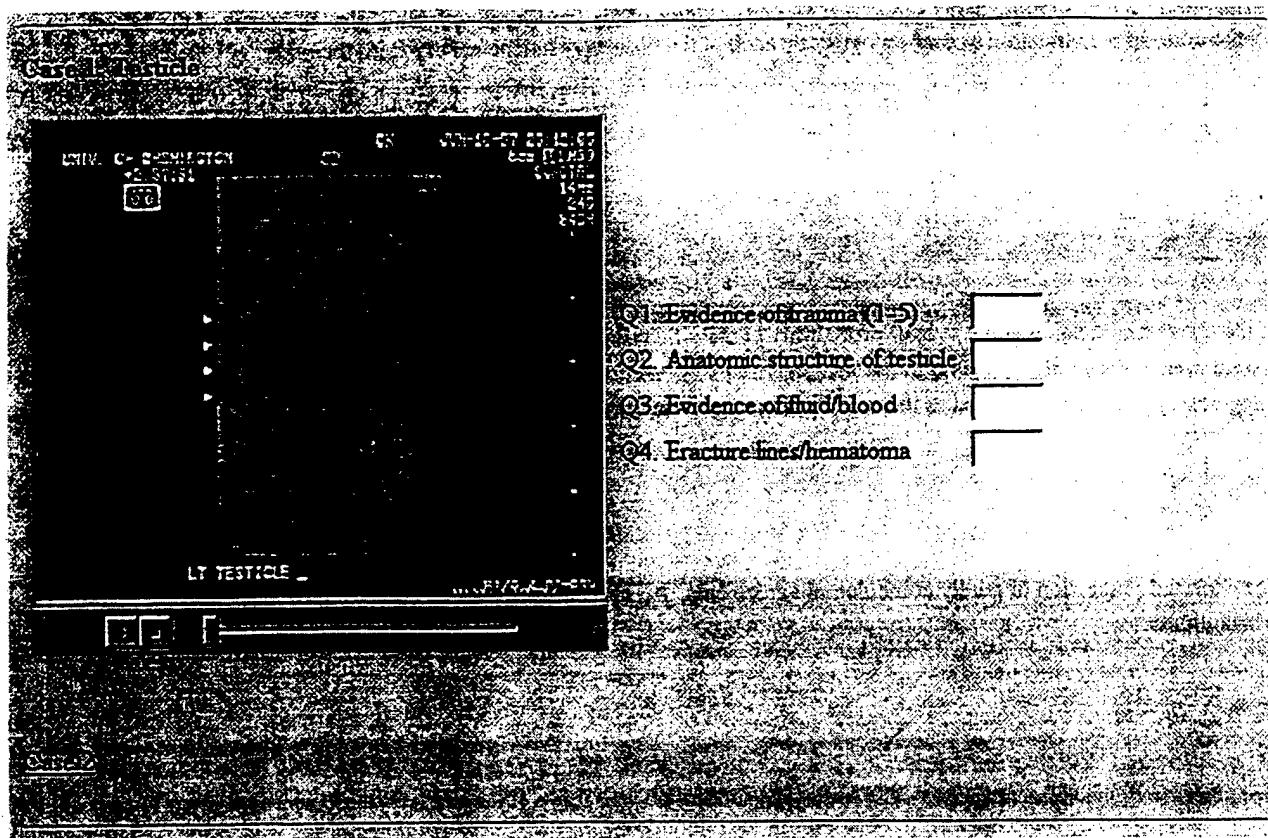


Figure 7. Videoclip display, control and associated key feature Likert evaluation questions for the testicular trauma videoclip.

## 9. KAPPA STATISTICAL ANALYSIS

To assess the extent, to which a given characterization of a subject is reliable, it is clear that we must have a number of subjects classified more than once, for example by more than one rater. The degree of agreement among the raters provides no more than an upper bound on the degree of accuracy present in the ratings, however. If the degree of agreement amongst readers is high, then there is a possibility that the ratings (i.e., average Likert score at each bandwidth) do in fact reflect the dimension they are purported to reflect (video quality versus bandwidth). If their agreement is low, on the other hand, then the usefulness of the ratings is severely limited, for it is meaningless to ask what is associated with the variable rated when one cannot even trust those ratings to begin with.

Kappa statistical analysis measures the degree of agreement between observers and between viewing assessment. Derivations of kappa statistics can be found in [8,9]. Herein, we restrict the presentation to the basic formulae employed in this study, first for two observers [8], and then for more than two observers [9].

### 9.1. Calculation for two observers:

Let  $N$  be the number of Likert scale evaluations that were rated by two independent observers (ultrasound radiologists) into  $k$  different categories (here one of the five Likert ratings;  $k = 5$ ). From the observers' responses, one can form a  $k \times k$  table where  $f_{ij}$  is the frequency of joint classification of the number of subjects classified to the  $i$ th category by the first observer and to the  $j$ th category by the second observer. These frequencies divided by  $N$  can be used as estimates for the appropriate probabilities of joint classification,  $p_{ij}$ :  $p_{ij} = f_{ij} / N$

Furthermore, similarly normalized sums of rows and columns of the joint frequency table give estimates of the overall probabilities of classification to each category by each of the observers independently from the other:

$$p_i = \sum_{j=1}^k p_{ij}, \text{ and} \quad (1)$$

$$p_j = \sum_{i=1}^k p_{ij}. \quad (2)$$

In the above formulae,  $p_i$  is the overall probability of classification of the  $i$ th category by the first observer, and  $p_j$  is the overall probability of classification to the  $j$ th category by the second observer. The observed proportional agreement on all categories,  $p_o$ , can be calculated as the sum of products of independent probabilities:

$$p_o = \frac{1}{N} \sum_{j=1}^k f_{jj}. \quad (3)$$

The expected proportion of purely coincidental agreements,  $p_c$ , can be calculated as the sum of products of independent probabilities:

$$p_c = \sum_{i=1}^k p_i \times p_i. \quad (4)$$

From these two, the value of kappa (  $\kappa$  ) is derived:

$$\kappa = \frac{p_o - p_c}{1 - p_c}. \quad (5)$$

Typically, the following descriptions are used for various ranges of kappa:

0.8 to 1.0: very good,  
0.6 to 0.8: good,  
0.4 to 0.6 moderate,  
0.2 to 0.4: fair, and  
0.0 to 0.2: poor.

In the above formulation, only perfect agreements contribute to  $p_o$ . However, when categories are ordered, one can include quantification (weighting) of the degree of agreement in the kappa calculations. A perfect agreement should receive a weighting of 1.0, while discrepancies in classifications by the two observers by one, two and up to  $k-1$  categories result in gradually decreasing weightings. In our analysis, we will employ linearly decreasing weights  $w_{ij}$  as in [8]:

$$w_{ij} = 1 - \frac{|i-j|}{k-1}. \quad (6)$$

The weighted observed,  $p_{wo}$ , and weighted expected  $p_{we}$ , proportions of agreement are calculated as:

$$p_{wo} = \frac{1}{N} \sum_{i=1}^k \sum_{j=1}^k w_{ij} \times f_{ij}, \text{ and} \quad (7)$$

$$p_{wc} = \sum_{i=1}^k \sum_{j=1}^k w_{ij} \times p_i \times p_j. \quad (8)$$

The weighted kappa,  $\kappa_w$ , is given by:

$$\kappa_w = \frac{p_{wo} - p_{wc}}{1 - p_{wc}} \quad (9)$$

The standard error of the weighted kappa,  $SE(\kappa_w)$ , can be calculated according to the formula given by Fleiss [9]:

$$SE(\kappa_w) = \frac{1}{(1 - p_{wc})\sqrt{N}} \sqrt{\sum_{i=1}^k \sum_{j=1}^k p_i p_j [w_{ij} - (w_i + w_j)]^2 - p_{wc}^2}, \text{ where} \quad (10)$$

$$w_i = \sum_{j=1}^k p_j w_{ij}, \text{ and} \quad (11)$$

$$w_j = \sum_{i=1}^k p_i w_{ij}. \quad (12)$$

## 8.2. Calculation of kappa for more than two observers

For the case of more than two observers, Fleiss [9] added new definitions of kappa values to the ones calculated for the observer pairs. These new kappas quantify the agreement within observer groups and within classification categories. Assuming  $m$  to be the number of observers in a group (or alternately the number of classifications per subject), with  $N$  and  $k$  to be the numbers of subjects and categories, respectively, the kappa for the  $j$ th group,  $\kappa_j$ , is defined as follows:

$$\kappa_j = 1 - \frac{\sum_{i=1}^N x_{ij}(m - x_{ij})}{Nm(m-1)p_j q_j}, \quad (13)$$

where  $x_{ij}$  is the number of classifications of the  $i$ th subject to the  $j$ th category,  $p_j$  is the proportion of all classifications that went into the  $j$ th category:

$$p_j = \frac{\sum_{i=1}^N x_{ij}}{\sum_{i=1}^N \sum_{j=1}^k x_{ij}} = \frac{\sum_{i=1}^N x_{ij}}{N \times m}, \text{ and} \quad (14)$$

$q_j$  is the complement of  $p_j$ , i.e.,  $q_j = 1 - p_j$ .

The overall kappa for the  $m$  observers is then given as:

$$\kappa = 1 - \frac{Nm^2 - \sum_{i=1}^N \sum_{j=1}^k x_{ij}^2}{Nm(m-1) \sum_{j=1}^k p_j q_j} \quad (15)$$

The standard errors of the intracategory and intraobserver group kappas,  $SE(\kappa_j)$  and  $SE(\kappa)$  can be estimated using the formula given by Fleiss [9]:

$$SE(\kappa_j) = \sqrt{\frac{2}{Nm(m-1)}}, \text{ and} \quad (16)$$

$$SE(\kappa) = \frac{\sqrt{2}}{\sum_{j=1}^k p_j q_j \sqrt{Nm(m-1)}} \sqrt{\left( \sum_{j=1}^k p_j q_j \right)^2 - \sum_{j=1}^k p_j q_j (q_j - p_j)} \quad (17)$$

## 10. LIKERT EVALUATION USING KAPPA STATISTICS

At this time, we only have results analyzed for the three physician pilot test that was recently completed. Graphically, the results of the pilot test confirm what was observed from the initial ACTS results, that there is indeed a shoulder at 384 kbps, above which, the perceived image quality only increases asymptotically (Fig 8). The two observer Kappa statistical results for the pilot study are given in Table XII, almost all of which indicate excellent agreement between the observers.

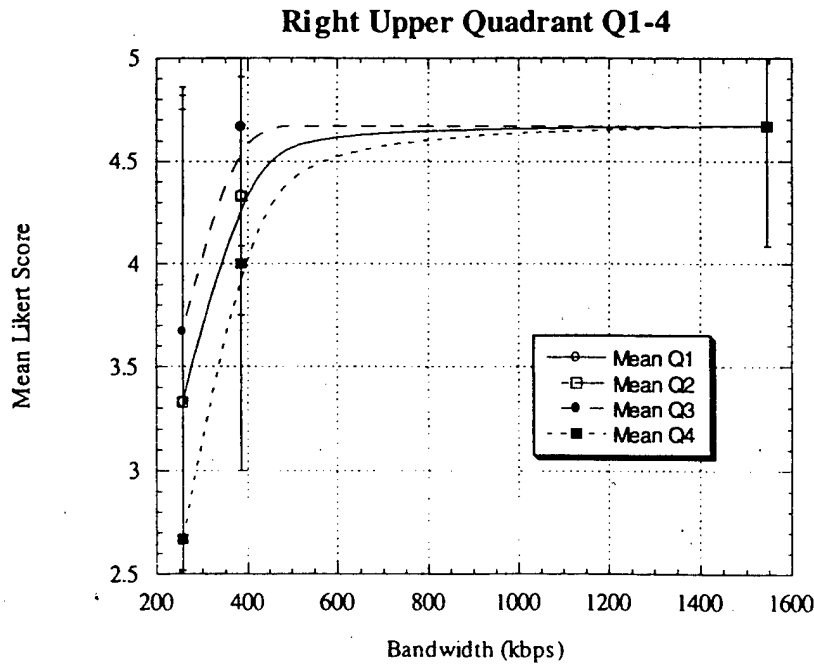


Figure 8. Plot of pilot test mean Likert Score versus bandwidth (256, 384 and 1544 kbps) for the first four questions in Table V.

Table XII. Weighted kappa scores for two physicians from the pilot study ( Equation 9).

Videoclip Anatomy	Kappa value (256 kbps)	Kappa value (384 kbps)	Kappa value (1544 kbps)
1. Right Upper Quadrant	0.75	0.87	0.75
2. Abdominal Cross Section	0.96	0.71	0.83
3. Early Pregnancy	0.85	0.85	0.80
4. Aorta Cross Section	0.88	0.82	0.82
5. Aorta Longitudinal View	0.76	0.76	0.94
6. Testicular Trauma	0.85	0.78	0.85

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### REFERENCES

- [1] Stewart BK, Carter SJ, Rowberg AH. Application of the Advanced Communications Technology Satellite for Teleradiology and Telemedicine. Proc SPIE 1995; 2435: 210-219.
- [2] Stewart BK, Carter SJ, Rowberg AH, Cook J, Abbe B, Pinck D. Real-time Compressed Video Ultrasound Using the Advanced Communications Technology Satellite. Proc SPIE 1996; 2711: 194-204.
- [3] Dallal I, Mustillo P. CCITT audiographics standards. Ed: Phillips D, Desrochers P. Proceedings of the Multimedia Communications '93, 1993; 213-5.
- [4] Liou ML. Overview of the p x 64 k bits/s video coding standard. Comm. of the ACM, 1991; 34(4):59-63.
- [5] Gold RH, Kangaroo H, Grant EG, Yaghmai I, Stewart BK, Mankovich NJ, Sayre JW, Dwyer SJ. Teleconferencing for cost-effective sharing of radiology educational resources: Potential and technical development. AJR 1993; 160: 1309-1311.
- [6] Meetz HK, Bebeau MJ and Thoma SJ. The validity and reliability of a clinical performance rating scale. J. Dent. Educ. 1988; 52(6): 290-297.
- [7] Merrill JM, Camacho Z, Laux LF, et al. Uncertainties and ambiguities: measuring how medical students cope. Med. Educ., 1994; 28(4): 316-322.
- [8] Altman DG. Practical Statistics for Medical Research (Chapman and Hall, London), 396-439 (1991).
- [9] Fleiss L. Statistical Methods for Rates and Proportions (John Wiley & Sons, New York), 213-235 (1981).



## Wavelet Compression of Ultrasound Video Streams for Teleradiology

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### Abstract

Future developments in teleradiology hinge on the delivery of real or near realtime images, sometimes across less than optimal bandwidth communication channels. Ultrasound, to achieve its greatest diagnostic value, needs to transmit not just still images but video as well. A significant amount of compression, however, maybe required to achieve near real-time video across limited bandwidths. This will inevitably result in degraded video quality.

A variety of compression algorithms are in wide spread use including H.261, H.323, JPEG (Joint Photographic Experts Group [1]), MPEG (Motion Picture Expert Group, [2]) and most recently wavelets. We have developed a suite of tools to evaluate each of these methods, and to identify potential areas where wavelet compression may have an advantage. In this particular study, we compare "motion-wavelet" compression to "motion-JPEG" (compression using the standard correlation coefficient and the normalized mean squared error, and found the motion wavelet technique slightly better.

### 1. Introduction

In order to achieve its greatest diagnostic value, ultrasound imaging must involve not only still images but video as well. The bandwidth demands of real time, or near real time, video are generally much greater than the capacity of typical intranet or Internet communication channels, and the images must therefore be highly compressed. "Lossless" compression is not enough: full frame video may have a bandwidth of 150 mega-bits per second (Mbps), while the bandwidth of a T-1 channel is about 1.5 Mbps. These kinds of application require "lossy" compression, in which the re-

sulting image quality is to some extent degraded by loss of information.

The degradations imposed by lossy compression produce blurring, loss of resolution, and "artifacts", any of which, if serious enough, may lead to misdiagnosis. The standards for still (JPEG) and video (MPEG) image compression produce well-known "blocking" artifacts under heavy compression, due to their block-oriented partitioning of each image. Wavelet compression techniques, on the other hand, do not produce block artifacts under lossy compression, and have found acceptance in such diverse fields as digital coronary angiography [3] and fingerprint archiving (FBI [4]).

Quantification of image quality degradation has a rich history in image processing and has involved a variety of metrics. Our group is developing the tools to apply both numerical figures-of-merit and more subjective receiver operating characteristic (ROC) type analyses, involving jury tests with experienced sonographers, to video clips, using wherever possible commercial solutions and off-the-shelf software. This approach leverages off the rapid growth of the PC-based commercial digital video market.

In this paper, we report on the numerical comparison between lossy compression with the "motion JPEG" technique and an analogous "motion wavelet" technique.

### 2. Motion JPEG versus Motion Wavelet

One video compression technique is to compress each frame separately. When the compression is effected with the JPEG algorithm, the technique is called "motion JPEG" [5]. We used the Video-for-Windows (VfW)-compliant motion-JPEG codec from Paradigm Matrix [6]. By analogy, compression effected by a wavelet-based technique will be called "motion wavelet": for this, we used the VfW-compliant ADV601 wavelet codec from Analog Devices [7]. This wavelet codec uses a 7,9 biorthogonal discrete wavelet transform followed by a quantizer and Huffman and run-length encoders. The Paradigm Matrix codec configures with a "quality" setting, the

ADV601 codec with a "bits-per-pixel" setting; both indirectly set the target compression ratio.

### 3. The Test Videos

Six reference videoclips were acquired using a Broadway video capture card [8] and stored on PC hard disk as Vfw AVI (audio-video interleaved) files. These clips, which are available on our website[9], are short excerpts of diagnostic ultrasound videos involving the following mix of anatomy and pathology:

1. Right upper quadrant (kidney, liver and Morison's pouch)
2. Abdominal cross section (pancreas, liver, aorta, inferior vena cava, splenic and renal vein, kidney and superior mesenteric artery)
3. Early pregnancy (inter-uterine pregnancy and viable fetus)
4. Aorta cross section
5. Aorta longitudinal view (aorta, superior mesenteric artery)
6. Testicular trauma

Each reference videoclip was acquired with 352x240 resolution in 24-bit RGB format, with 30 frames per second. Each videoclip was then (a) transcoded into a motion-JPEG-compressed AVI using the Asymetrix Digital Video Producer (DVP [10]) and (b) transcoded into a motion-wavelet-compressed AVI using a custom transcoder [9]. The compressed AVI files were then all transcoded into uncompressed AVIs using DVP and finally "ripped" into individual device-independent bitmap (DIB) files, one file per frame, using the DOS freeware utility AVIRIP [11]. A sample frame from videoclip 1 is shown in figures 1 - 3.

Two metrics were used to compare the frames in the compressed AVI videoclips against the reference AVI videoclips: a correlation coefficient  $\rho$  and the normalized mean square error (NMSE). These were computed using

$$\rho^{(i)} = \frac{\frac{1}{N} \sum_{j,k} f_{j,k}^{(i)} g_{j,k}^{(i)}}{\sqrt{MSS(f^{(i)})} \sqrt{MSS(g^{(i)})}}$$

and

$$NMSE^{(i)} = \frac{MSE(f^{(i)}, g^{(i)})}{\sqrt{MSS(f^{(i)})} \sqrt{MSS(g^{(i)})}},$$

where the mean squared error  $MSE$  is

$$MSE(f^{(i)}, g^{(i)}) = \frac{1}{N} \sum_{j,k} |f_{j,k}^{(i)} - g_{j,k}^{(i)}|^2,$$

the "mean squared signal"  $MSS$  is

$$MSS(f^{(i)}) = \frac{1}{N} \sum_{j,k} |f_{j,k}^{(i)}|^2,$$

$f_{j,k}^{(i)}$  is the  $(j,k)$ th pixel of the  $i$ th reference frame and  $g_{j,k}^{(i)}$  is the  $(j,k)$ th pixel of the  $i$ th lossy compressed-decompressed frame. Each frame is assumed to have  $N$  total pixels.

The "raw" values  $\rho^{(i)}$  and  $NMSE^{(i)}$  were computed for each frame pair, and the raw estimates then averaged over all frame pairs in the videoclips to obtain the reported values.

### 4. Results

The configurations used for the codecs are shown in table 1. The average bandwidth was essentially the ratio of the compressed AVI file size in kilobytes (KB) to the clip duration. Visual inspection indicated that an average bandwidth of about 1500 Kbps (comparable to a T-1 LAN connection) was more-or-less the lower limit for useful compression. The quantizing algorithms in the two codecs could only be set approximately by their respective configuration parameters: the settings shown in table 1 represent the closest fit to 1500 Kbps achieved via trial-and-error.

The correlation coefficients are shown in table 2 and the NMSE in table 3. The typical compression rates for these videoclips was about 38:1 and produced visually lossy image quality. The two figures-of-merit, the normalized mean squared error and the correlation coefficient, were nearly identical, with a slight improvement shown for motion-wavelet in both quantities.

clip	# of frames	duration ([secs])	motion- JPEG		motion wavelet	
			quality	ave. bandwidth ([Kbps])	bits-per-pixel	ave. bandwidth ([Kbps])
1.	720	24.24	55	1590	0.406	1584
2.	690	23.23	40	1545	0.375	1561
3.	398	13.28	23	1527	0.406	1789
4.	600	20.20	35	1647	0.375	1580
5.	389	13.13	50	1576	0.468	1614
6.	660	22.22	27	1524	0.375	1683

Table 1. Videoclip details and codec configurations.

clip	motion-JPEG	motion-wavelet
1.	0.9979	0.9986
2.	0.9878	0.9933
3.	0.9914	0.9954
4.	0.9949	0.9968
5.	0.9907	0.9935
6.	0.9733	0.9824

Table 2. Correlation coefficients, motion-JPG versus reference, motion-wavelet vs reference.

clip	motion-JPEG	motion-wavelet
1.	0.0046	0.0031
2.	0.0240	0.0136
3.	0.0174	0.0094
4.	0.0105	0.0065
5.	0.0193	0.0131
6.	0.0536	0.0353

Table 3. Normalized mean-square error, motion-JPG versus reference, motion-wavelet versus reference.

## 5. Conclusions

These tests estimate two figures-of-merit over short video clips and found them nearly identical, with a slight improvement shown for motion-wavelet compression. In previous work, using a metric sensitive to block artifacts [12], Ho et al concluded that for similar amounts of lossy compression in coronary and neuro angiograms the block-encoded methods introduced significantly more block artifacts. This would suggest that the motion wavelet codec would perform even better than the mo-

tion JPEG codec based on a block artifact metric.

However, due to the visual integration performed unconsciously by a trained observer, it is not clear to what extent these single frame figures-of-merit extend into the video regime. The next step is therefore to perform jury tests on these lossy results to determine the amount of degradation ultrasound videoclips can suffer and still remain useful diagnostic tools.

Of course, in a broader context, this so-called "intraframe" (or I-frame) compression technique does not exploit the high redundancy in image content between frames, and therefore cannot achieve the same compression rates as, say, MPEG, for a given amount of image degradation. The integration of wavelet-based compression with interframe decorrelation procedures is still an emergent field, with no clear standards yet. Our results strongly suggest, however, that such codecs might prove to be a key feature of low bandwidth delivery of diagnostic ultrasound video.

## References

1. G. K. Wallace, "The JPEG still picture compression standard", *Commun. of the ACM*, vol. 34, pp 30-44, April 1991.
2. D. Le Gall, "MPEG: A video compression standard for multimedia applications", *Commun. of the ACM*, vol. 34, pp 46 - 58, April, 1991.

3. B. K. T. Ho *et al.*, "Video Compression of Coronary Angiograms Based on Discrete Wavelet Transform with Block Classification", *IEEE Trans. in Med. Imaging*, vol. 15, no. 6, pp 814 - 823, December 1996.
4. Chris Brislawn, online documentation at URL <http://www.c3.lanl.gov/~brislawn/FBI/FBI.html>, last updated 7/12/96.
5. J. F. McGowan, "AVI-FAQ", online document with URL <http://www.rahul.net/jfm/aviframe.html>. Latest update dated 11/12/97.
6. Paradigm Matrix, online company and product information at URL <http://www.pmatrix.com>, last updated 12/11/96.
7. Analog Devices, online documentation at URL <ftp://ftp.analog.com/pub/dsp/adv601/>. The Vfw codec is supplied as freeware to support their ADV601 wavelet compression chip, [http://www.analog.com/products/descriptions/2011\\_0.html](http://www.analog.com/products/descriptions/2011_0.html).
8. Online product information at URL <http://www.b-way.com>, last updated 6/27/97.
9. Online Web page at URL: <http://fibonacci.rad.washington.edu>. The MPEG-encoded versions of the video clips are found by following <The Ultrasound Compression vs. Dx Quality test> hyperlink. The ADV601 transcoder is found via the <The wavelet video compression page> link.
10. Online product information at URL <http://www.asymetrix.com>, 1997 - 1998.
11. M. Negus, AVIRIP.EXE, part of the online CONVMPEG3 freeware kit available at URL <http://www.powerweb.de/mpeg/msdos.html>.
12. B. K. T. Ho, *et al.*, "Video compression algorithm for dynamic angiographic images", *SPIE Proc. Medical Imaging*, Newport Beach, CA., vol. 2164, pp 302 - 309, February 1994.



Figure 1. Frame 211 from videoclip 1, original reference



Figure 2. Frame 211 from videoclip 1, compressed with the motion-JPEG codec, quality = 55.

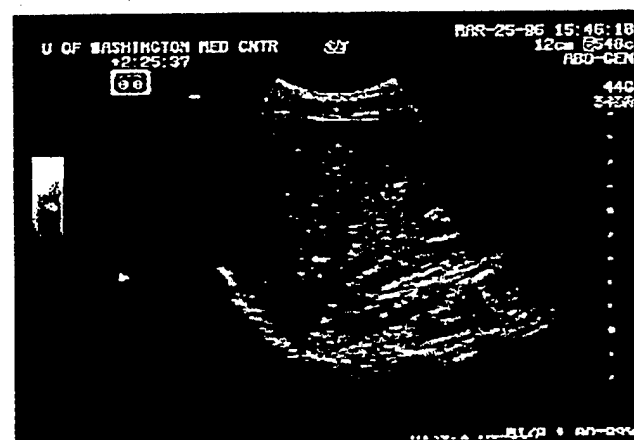


Figure 3. Frame 211 from videoclip 1, compressed with the ADV601 codec at 0.406 bits-per-pixel.

# PROCEEDINGS

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## ***1998 IEEE INTERNATIONAL CONFERENCE ON INFORMATION TECHNOLOGY APPLICATIONS IN BIOMEDICINE***

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### **ITAB '98**

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**16–17 May 1998**

**Marriott Hotel, Washington DC**

**Edited by**

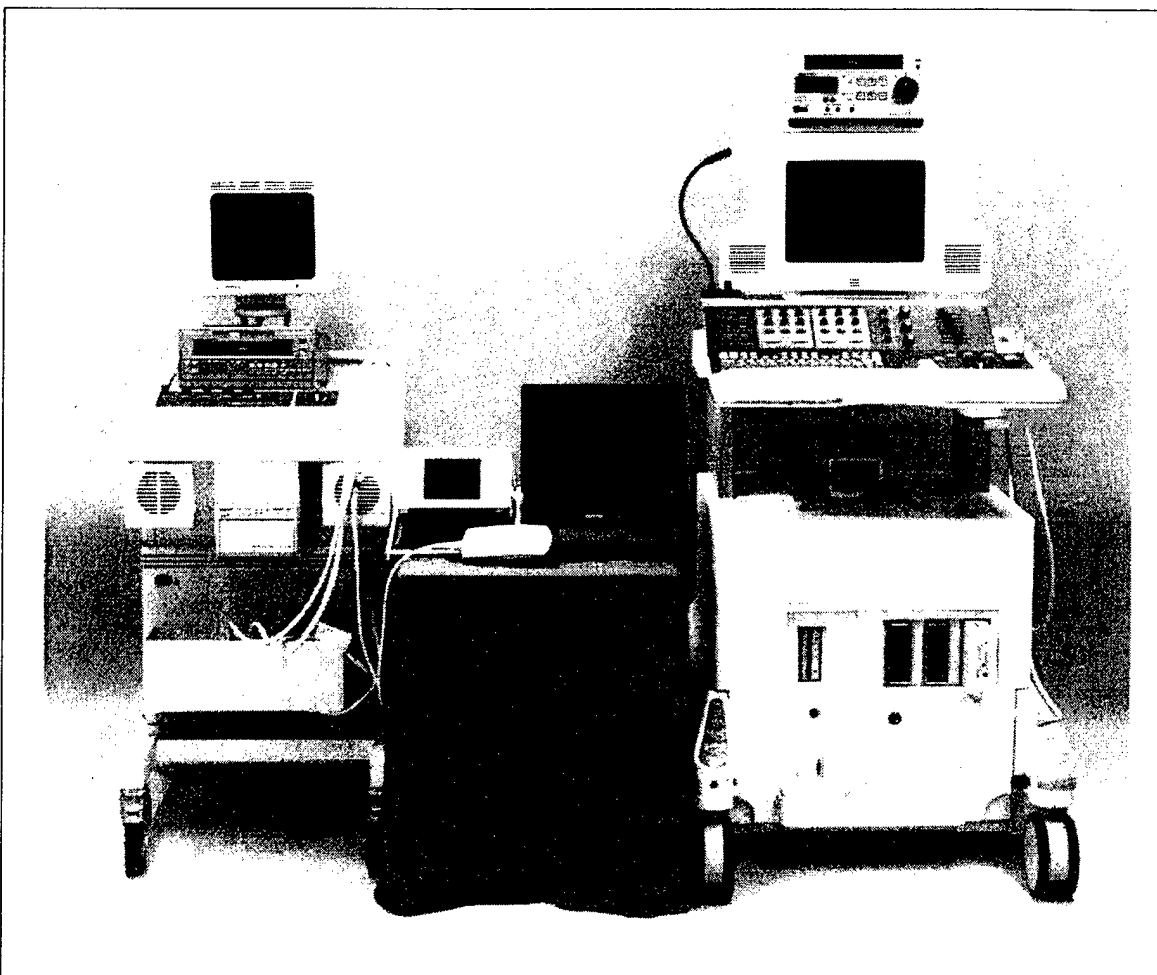
**Swamy Laxminarayan – *NextGen Internet USA and New Jersey Institute of Technology*  
Evangelia Micheli-Tzanakou *Rutgers – University, New Jersey***

## **APPENDIX B**

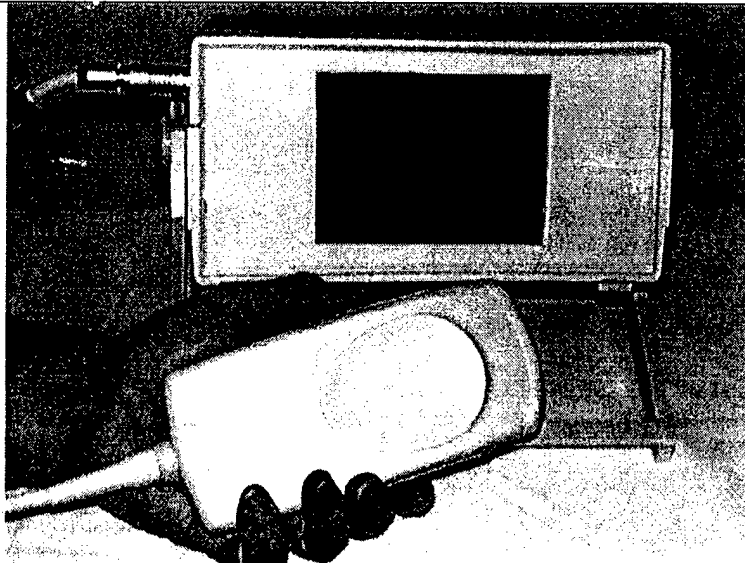


SonoSite 180

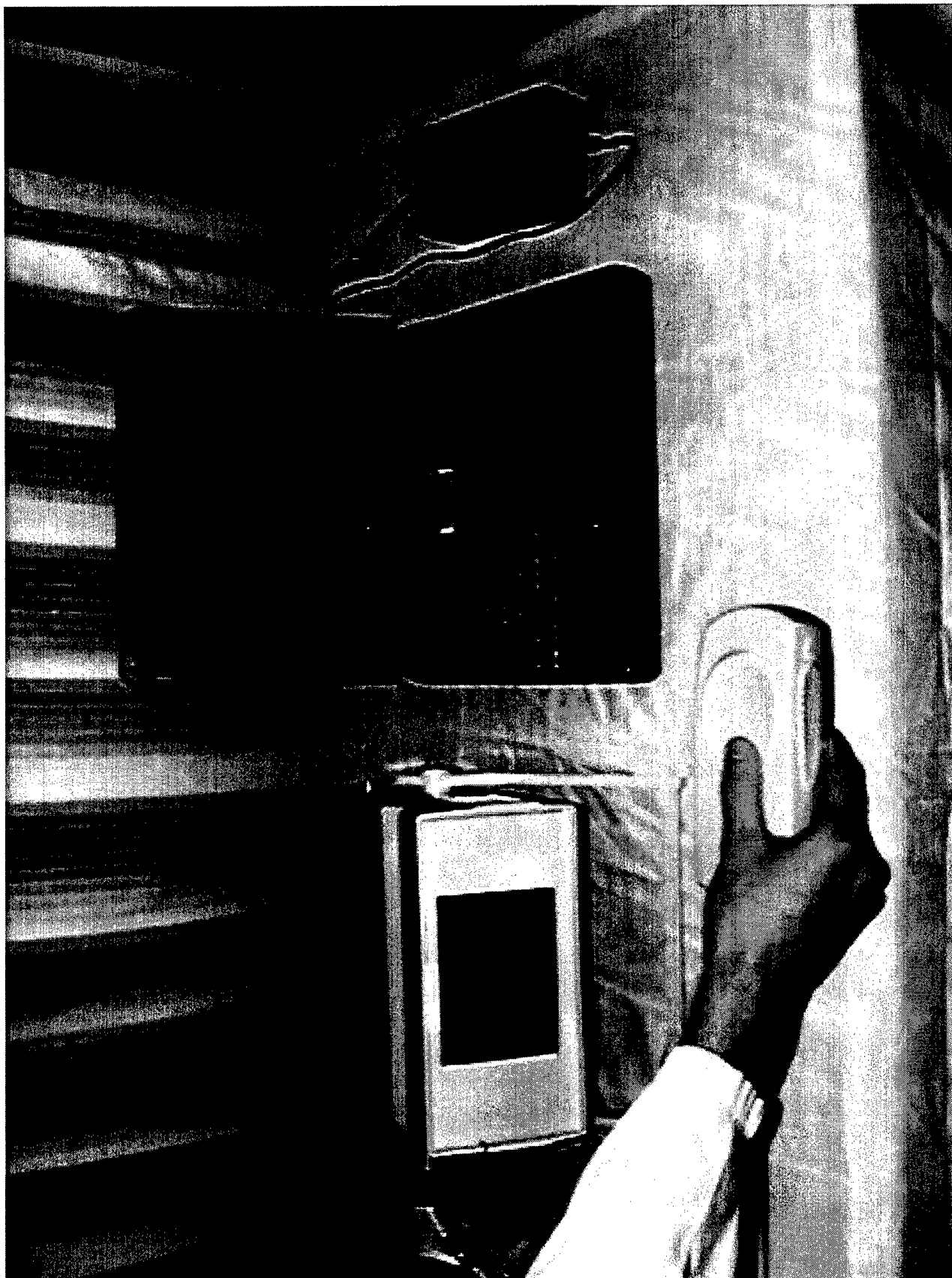




DARPA HHU C60 prototype contrasted with two commercial imaging systems marketed by ATL.



Close up view of the HHU C60 probe assembly (held in an investigators hand) and the display unit.



DARPA C60 PROTOTYPE

# **HHU DARPA C60 PROTOTYPE TESTING**

## **Testing and Comparison Using:**

- 1) HHU C60
- 2) ATL UM4
- 3) ATL HDI 3000

**C60 and UM4 Tested with and without Telemetry**

**(Telemedicine using Internet)**

# **CLINICAL TESTING**

Evaluations (70) were performed on (10) Subject  
Volunteers:  
(9) Normal and (1) Peritoneal Dialysis with Fluid.

## **Clinical Subjective Preference Testing**

- Likert 1-5 Scale (5=Best or Highest Rating, 1=Worst or Lowest).
- Evaluations Performed by (4) Radiologists with Expertise in Diagnostic US and (2) Expert Lead Sonographers.
- US Scans Performed by Examiners from the Novice to Expert Level.

Clinical Subjective Preference Testing  
DARPA - UW Radiology

Right Upper Quadrant

Please rate clinical image quality using the 1-5 scale (5 = best, 1 = worst)

1. Visualization of kidney/ liver contour: [4.40]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

2. Fluid visualization: (i.e. R/O significant fluid/blood in Morison's pouch) [4.50]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

3. Normal Respiratory Motion: [4.75]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

4. Comparative echogenicity: (i.e. liver>kidney) [4.00]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

5. R/O hydronephrosis: [4.40]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

6. R/O significantly dilated biliary ducts: [4.18]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

7. Gall Bladder visualization: [4.56]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

Overall

Avg.

[4.40]

US Equipment: HHU Prototype C 60 - Tel Med

Other: \_\_\_\_\_

Clinical Subjective Preference Testing  
DARPA - UW Radiology

Right Upper Quadrant

Please rate clinical image quality using the 1-5 scale (5 = best, 1 = worst)

1. Visualization of kidney/ liver contour: [4.63]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

2. Fluid visualization: (i.e. R/O significant fluid/blood in Morison's pouch) [4.70]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

3. Normal Respiratory Motion: [4.76]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

4. Comparative echogenicity: (i.e. liver>kidney) [4.52]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

5. R/O hydronephrosis: [4.69]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

6. R/O significantly dilated biliary ducts: [4.62]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

7. Gall Bladder visualization: [4.61]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

Overall  
Avg.  
[4.65]

US Equipment: HHU Prototype C 60

Other: \_\_\_\_\_

Clinical Subjective Preference Testing  
DARPA - UW Radiology

Right Upper Quadrant

Please rate clinical image quality using the 1-5 scale (5 = best, 1 = worst)

1. Visualization of kidney/ liver contour: [4.50]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

2. Fluid visualization: (i.e. R/O significant fluid/blood in Morison's pouch) [4.67]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

3. Normal Respiratory Motion: [4.83]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

4. Comparative echogenicity: (i.e. liver>kidney) [4.17]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

5. R/O hydronephrosis: [4.71]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

6. R/O significantly dilated biliary ducts: [4.67]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

7. Gall Bladder visualization: [4.60]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

Overall

Avg.  
[4.59]

US Equipment: HHU Prototype

Other: ATL UM4 & TelMed

Clinical Subjective Preference Testing  
DARPA - UW Radiology

Right Upper Quadrant

Please rate clinical image quality using the 1-5 scale (5 = best, 1 = worst)

1. Visualization of kidney/ liver contour:

[4.80]

Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

2. Fluid visualization: (i.e. R/O significant fluid/blood in Morison's pouch)

[4.70]

Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

3. Normal Respiratory Motion:

[4.80]

Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

4. Comparative echogenicity: (i.e. liver>kidney)

[4.70]

Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

5. R/O hydronephrosis:

[4.80]

Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

6. R/O significantly dilated biliary ducts:

[4.80]

Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

7. Gall Bladder visualization:

[4.71]

Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
Good Moderate Fair Slightly useful Not Useful

Overall

Avg.

[4.76]

US Equipment: HHU Prototype

Other: ATL UM4



Clinical Subjective Preference Testing  
DARPA - UW Radiology

Right Upper Quadrant

Please rate clinical image quality using the 1-5 scale (5 = best, 1 = worst)

1. Visualization of kidney/ liver contour: [5.00]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1 .....  
Good Moderate Fair Slightly useful Not Useful

2. Fluid visualization: (i.e. R/O significant fluid/blood in Morison's pouch) [5.00]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1 .....  
Good Moderate Fair Slightly useful Not Useful

3. Normal Respiratory Motion: [5.00]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1 .....  
Good Moderate Fair Slightly useful Not Useful

4. Comparative echogenicity: (i.e. liver>kidney) [5.00]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1 .....  
Good Moderate Fair Slightly useful Not Useful

5. R/O hydronephrosis: [5.00]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1 .....  
Good Moderate Fair Slightly useful Not Useful

6. R/O significantly dilated biliary ducts: [5.00]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1 .....  
Good Moderate Fair Slightly useful Not Useful

7. Gall Bladder visualization: [5.00]  
Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1 .....  
Good Moderate Fair Slightly useful Not Useful

Overall

Avg.

[5.00]

US Equipment: HHU Prototype \_\_\_\_\_

Other: ATL HDI 3000

**Clinical Subjective Preference Testing  
DARPA-UW**

**HHU Prototype C 60**

Please rate clinical image quality using the 1-5 scale (5=Best, 1=Worst)

5.....4.....3.....2.....1  
Good                      Moderate                      Fair                      Poor                      Unacceptable

**HHU C60 Prototype**

**LCD DISPLAY**

Viewing Angle/Axis	<u>4.32</u>
Diagnostic Quality/Resolution	<u>4.29</u>
Brightness	<u>3.87</u>
Contrast	<u>3.97</u>
Screen Size	<u>4.23</u>
Glare/Reflection	<u>4.35</u>
Lag/Delay	<u>4.52</u>

	UM4 *		HDI 3000**
TRANSDUCER SIZE	5.0	<u>3.64</u>	5.0
EASE OF USE ***	4.92	<u>3.54</u>	5.0
EXAM TIME	4.92	<u>4.26</u>	5.0

## Clinical Subjective Preference Testing DARPA - UW Radiology

Please rate the following using the 1-5 scale (5 = highest, 1= lowest) for this telemedicine session.

Skill level of remote examiner (please circle one):

novice.....minimum US experience.....moderate US experience.....expert

1. Value of Image of Scanhead / Patient (In addition to US image): [4.80]

5.....4.....3.....2.....1  
very helpful      moderately helpful      fairly helpful      slightly helpful      not helpful

2. Value of Graphic Overlay: [4.20]

5.....4.....3.....2.....1  
very helpful      moderately helpful      fairly helpful      slightly helpful      not helpful

3. Audio Channel (Necessary / Helpful): [5.00]

5.....4.....3.....2.....1  
very helpful      moderately helpful      fairly helpful      slightly helpful      not helpful

4. Resolution vs. Frame Rate (check one):

100% Prefer higher resolution

0 % Prefer higher frame rate (fps)

## Clinical Subjective Preference Testing DARPA - UW Radiology

Please rate the following using the 1-5 scale (5 = highest, 1= lowest) for this telemedicine session.

Skill level of remote examiner (please circle one):

novice.....minimum US experience..........moderate US experience.....expert

1. Value of Image of Scanhead / Patient (In addition to US image):

[2.63]

5.....4.....3.....2.....1  
very helpful    moderately helpful    fairly helpful    slightly helpful    not helpful

2. Value of Graphic Overlay:

[3.69]

5.....4.....3.....2.....1  
very helpful    moderately helpful    fairly helpful    slightly helpful    not helpful

3. Audio Channel (Necessary / Helpful):

[5.00]

5.....4.....3.....2.....1  
very helpful    moderately helpful    fairly helpful    slightly helpful    not helpful

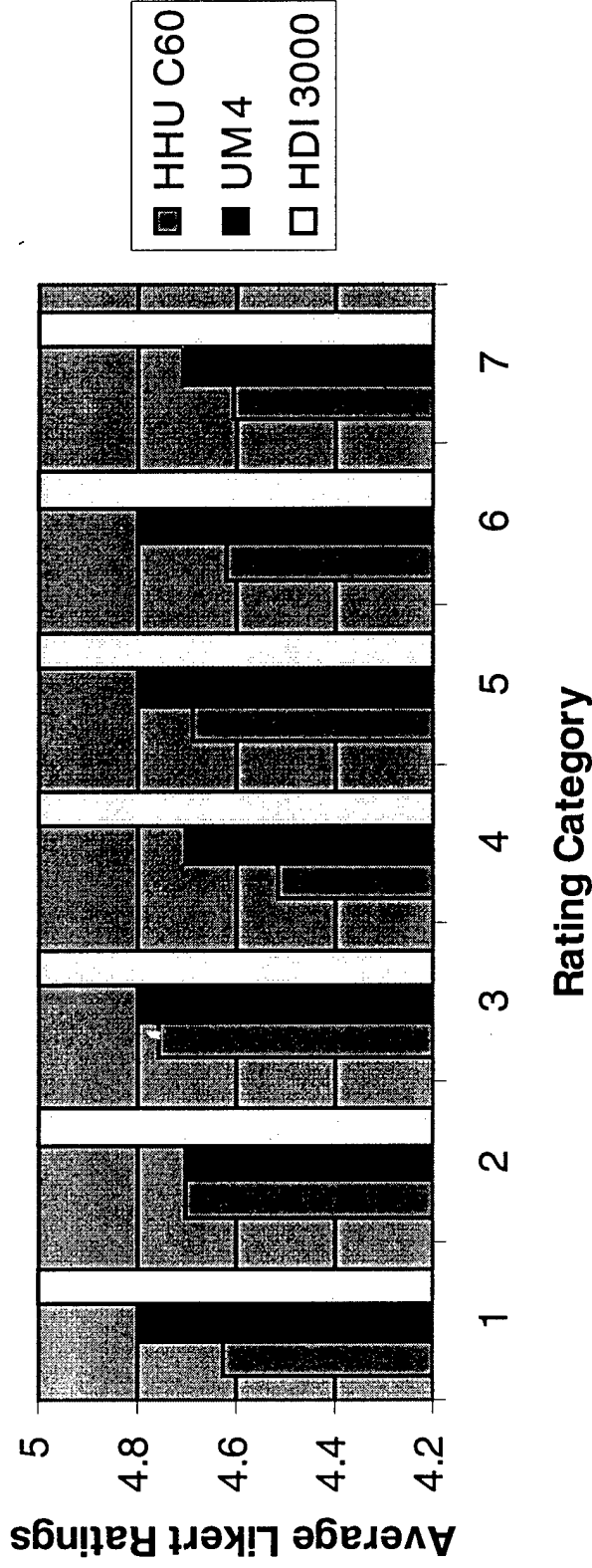
4. Resolution vs. Frame Rate (check one):

100% Prefer higher resolution

0% Prefer higher frame rate (fps)

# Subjective Clinical Image Quality

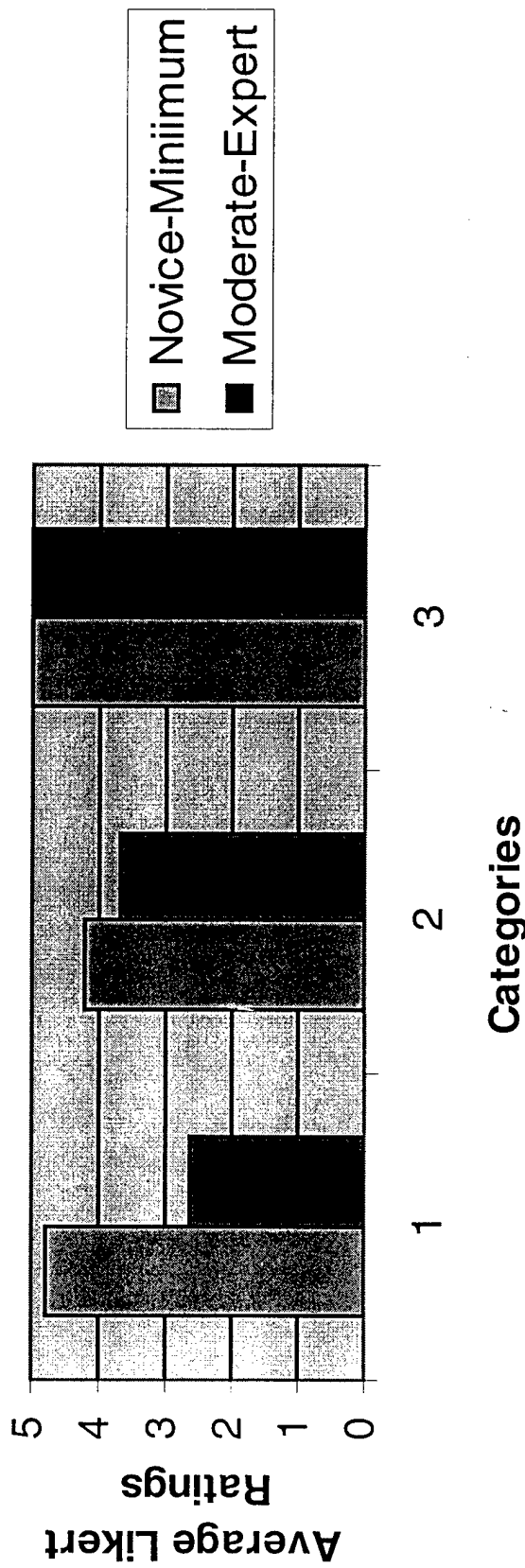
(70 Evaluations on 10 Subjects )



- 1- Visualization of kidney/liver contour
- 2- Fluid visualization: (i.e. Rule Out significant fluid/blood in Morison's pouch)
- 3- Normal Respiratory Motion
- 4- Comparative echogenicity: (i.e. liver>kidney)
- 5- Rule Out hydronephrosis (dilated kidney)
- 6- Rule Out significantly dilated biliary ducts
- 7- Gall bladder visualization

Scale: 5 ..... 4 ..... 3 ..... 2 ..... 1  
 Good Moderate Fair Slightly Useful Not Useful

# Subjective Comparison of the Advantages of Telemedicine Features



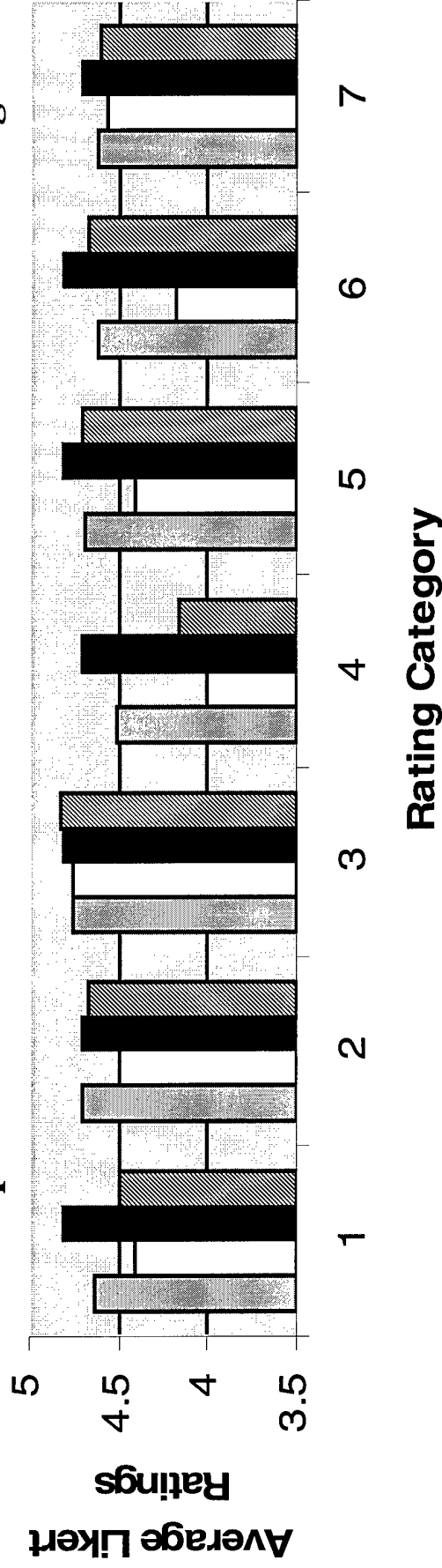
- 1- Value of Image of Scanhead/Patient (In addition to US image)
- 2- Value of Graphic Overlay
- 3- Audio Channel (Necessary/Helpful)

Scale: 5.....4.....3.....2.....1  
 Good Moderate Fair Slightly Useful Not Useful

# Subjective Clinical Image Quality

HHU C60 □ HHU C60 (telmedicine) ■ UM 4 ▨ UM 4 (telmedicine)

Comparison Between Direct and Telemedicine Transmitted Images



- 1- Visualization of kidney/liver contour
- 2- Fluid visualization: (i.e. Rule Out significant fluid/blood in Morison's pouch)
- 3- Normal Respiratory Motion
- 4- Comparative echogenicity: (i.e. liver>kidney)
- 5- Rule Out hydronephrosis (dilated kidney)
- 6- Rule Out significantly dilated biliary ducts
- 7- Gall bladder visualization

Scale: 5.....4.....3.....2.....1  
 Good Moderate Fair Slightly Useful Not Useful

# LCD Display

- Viewing Angle/Axis - 4.32
- Diagnostic Quality/Resolution - 4.29
- Brightness - 3.87
- Contrast - 3.97
- Screen Size - 4.23
- Glare/Reflection - 4.35
- Lag/Delay - 4.52

## Transducer Size

- 3.64

## Ease of Use

- 3.54

## Examination Time

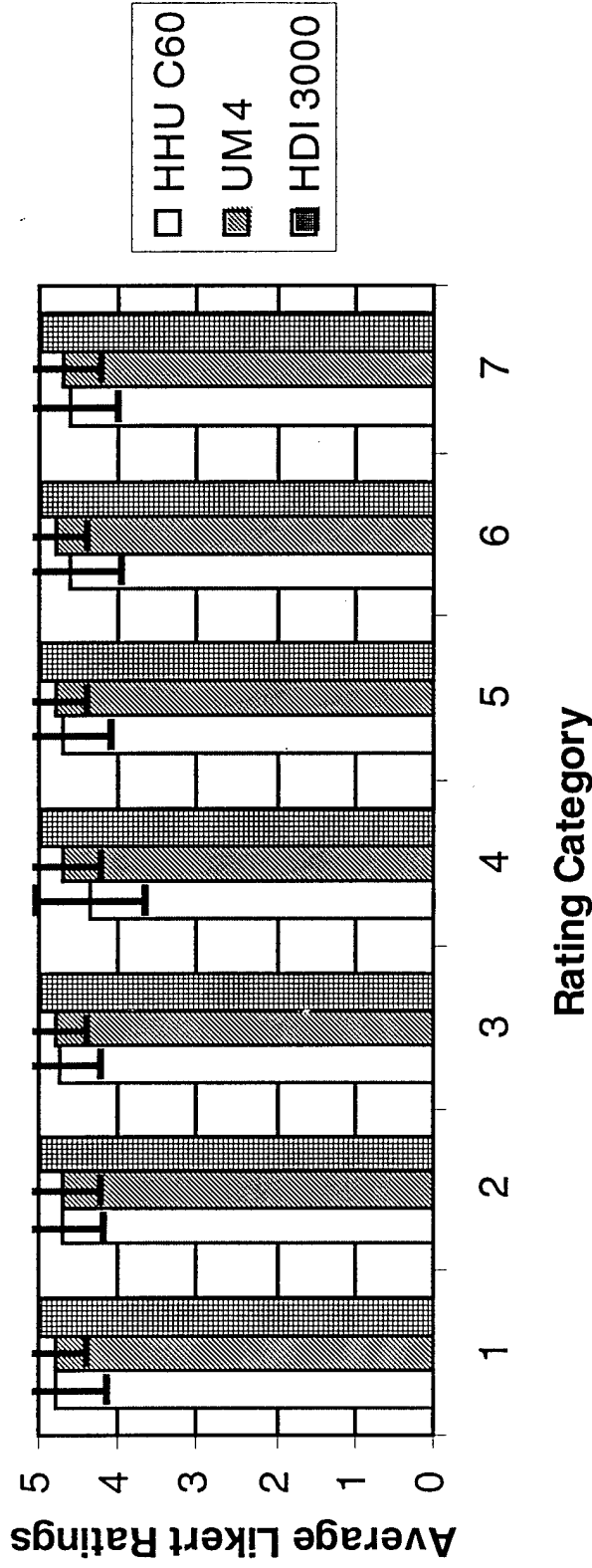
- 4.26

Scale: 5.....4.....3.....2.....1  
Good Moderate Fair Slightly Useful Not Useful



# Subjective Clinical Image Quality

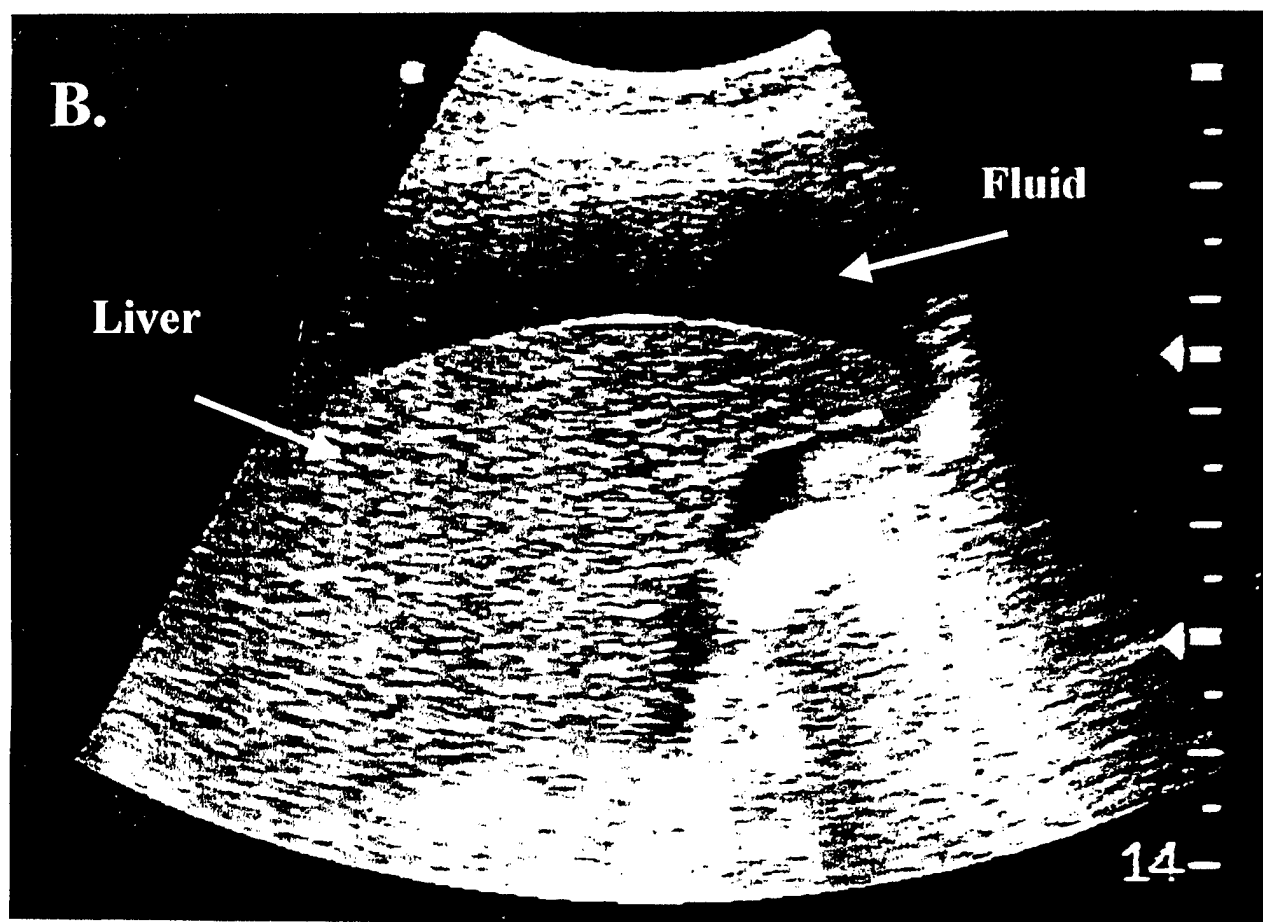
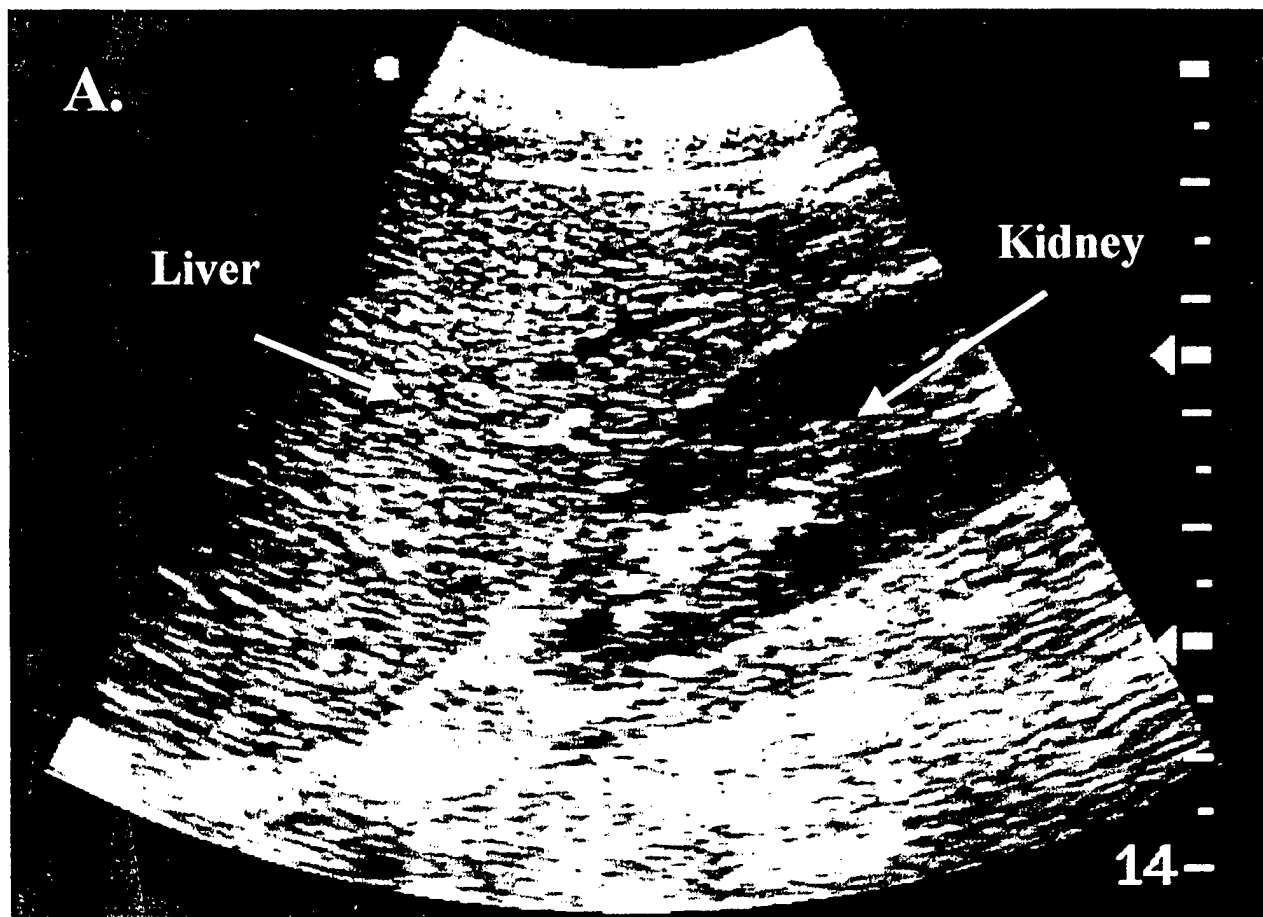
(70 Evaluations on 10 Subjects )



- 1- Visualization of kidney/liver contour
- 2- Fluid visualization: (i.e. Rule Out significant fluid/blood in Morison's pouch)
- 3- Normal Respiratory Motion
- 4- Comparative echogenicity: (i.e. liver>kidney)
- 5- Rule Out hydronephrosis (dilated kidney)
- 6- Rule Out significantly dilated biliary ducts
- 7- Gall bladder visualization

Scale: 5.....4.....3.....2.....1

Good    Moderate    Fair    Slightly Useful    Not Useful



## Fort Lewis 18th MASH Unit Visit — Overall Summary

**Acceptability:** Personnel interviewed were enthusiastic about the use of this new imaging device during situations of military action.

**Possible levels of application:** In the triage area of a MASH unit for assessment of abdominal trauma (detection of fluid in abdomen), and intra-operatively for shrapnel detection as well as identification of specific damage to internal organs for operative repair.

**Sterilization:** Rapid and easy sterilization of the scanhead is important for use on a high volume of wounded persons. Use of a plastic sheath on the probe recommended to protect it from coming in direct contact with blood and body fluids. Scanhead should be capable of being cold sterilized with readily available disinfectants such as Betadine.

**Impedance matching gel:** The matching gel, which is crucial for conducting an ultrasound scan could be stored in the pharmacy refrigerators in extremely hot environments. The matching gel could also be procured in a powder form from certain vendors, the bulk of it being stored as such, at a time, a portion of it prepared for use.

**Portability:** Device should be fully portable — it should not be connected to a wall mount, or be connected on to any static piece of equipment (e.g., for data storage) with cables.

**Design:** Device should be rugged and capable of withstanding extreme temperatures (sub-zero up to 55°C), humidity, and dust. It should be packaged in a hard-shell case for safe transportation with other pieces of equipment when the military unit is in transit.

**Power considerations:** Outlets for standard 115 V, 60 Hz were available in MASH units for charging the ultrasound device batteries. However, the variability of plug-in receptacles and power supply in various situations, such as, 24 V DC in the transport vehicle, should be kept in mind, while planning the use of the device.

**Display and controls:** Lighting in the MASH unit we visited would possibly be adequate for the use of liquid crystal displays. More on this is reported elsewhere. The issue of whether the display should be separate from the scanhead, or should it be head mounted needs to be decided. Controls on the device should be simple in terms of controlling the depth and transmit-receive gain of a single frequency scanning transducer. Controls should be such that no dust or liquid can seep inside the device. The scanhead should be easy to grip with one hand, leaving the other hand free for manipulating the controls and the wounded.

**Documentation and image storage:** It will be crucial for the personnel performing the ultrasound examination to document their findings so that the surgical team can exploit the information. Notes, comments on a hardcopy schematic made by the sonographer as well as a Polaroid copy of important frames are "low-tech" options. Transfer of information through telemetry into the OR or to a remote site for expert evaluation are possible high-tech options.

**Training:** Adequate training of personnel to use the ultrasound imaging modality for trauma evaluation is key to the success of this project. The radiologist technician in addition to a couple of selected medics, could be trained to perform an ultrasound exam based on a simplified protocol. Interactive training tools (like CD-ROM) could be used, followed by hands-on instruction sessions. A basic understanding of the cross sectional anatomy is important for surgeons in order to interpret the sonographic images.



head injury

pneumothorax

cardiac

abdominal trauma

vascular

fx

Expansion of clinical capabilities

## **Shrapnel Detection**

- **The real problem is Foreign Body detection**
  - **Shrapnel is subset**
    - **and our interest has been in material difficult to detect with X-ray.**
- **Key Consideration of Foreign Body Detection**
- **38 % are overlooked in the initial examination**
  - **Missed foreign bodies has been reported to be 2<sup>nd</sup> leading cause of malpractice suits against ER physicians**
  - **55% of the world's antipersonnel mines are encased in radiolucent material**
  - **Radiolucent material is detectable with ultrasound**
  - **Is it necessary to detect Foreign Bodies?**
  - **Foreign Bodies can migrate and can have delayed reaction**
  - **Is it necessary to remove a Foreign Body?**
  - **How easy is it to detect various foreign bodies with ultrasound**

### **General findings:**

- **The presence of air with the foreign body made it more visible.**
- **Less air occurred with high speed object**

## **Variables Involved in Ultrasound Detection of Foreign Bodies and Summary of what was learned:**

- **Tissue Region**
- **Ultrasound contrast was important.**  
    **Presence of normal bright specular reflectors could hide foreign bodies**
- **Difficulty: Skin > Muscle > Kidney > Heart>Liver> Spleen**
- **The Material (some examples):**
  - **Most Difficult:** Glass, A Few Plastics, Button, Thin Metal Wire
  - **Medium Difficulty:** Shoelace, Shoe Sole, Cardboard, Coin, Plastic Mine, Bamboo Stick, Green Wood
  - **Easy:** Dry Wood, Cement, Leather, Many Types of Plastics, Leather, Bakelite, Ceramic, Brick, Sand, Dirt, Rock, Feces
- **The Shape:**
  - **Most Difficult:** Smooth, Particularly Flat Polished
  - **Easiest:** Rough Surface
- **The Size: The larger the easier**
- **Ultrasound Imaging Frequency:**
  - **Generally the Higher the better**
  - **But depends on how deep into the tissue the object is.**

### **Ultrasound Scan Head Configuration:**

- **Linear Array > Curved Linear> Phased Array**
- **For example: L10-5 > C4-2> P5-3**

**What are some of the detection cues?**

**Bright echoes sometimes followed by shadowing**

**Ringling or Comet Tails for Bullets or Metals**

**Dark Shadows**

**Scan from several angles is important**

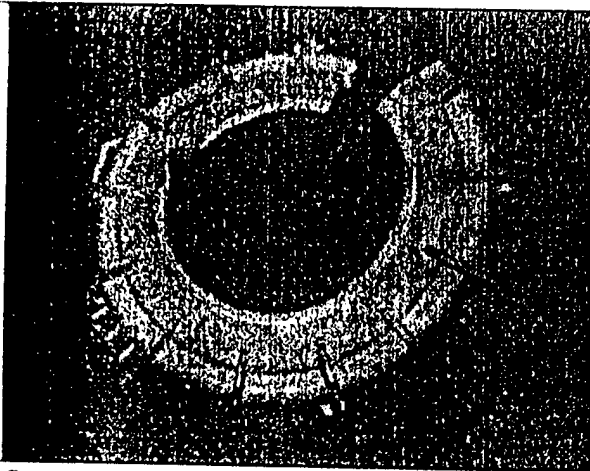
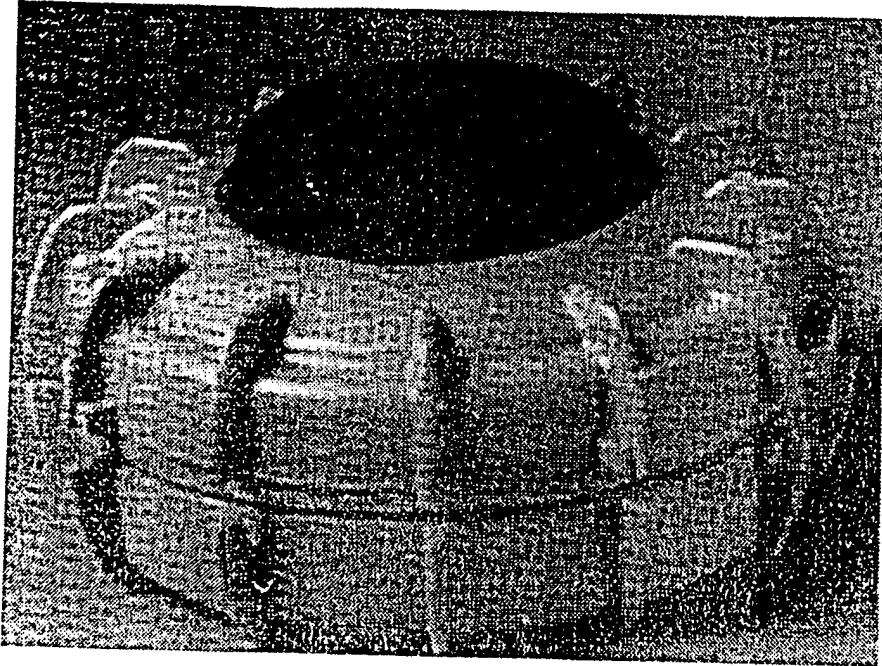
## CONCLUSIONS

Detection	<ul style="list-style-type: none"><li>• Generally by hyperechoic appearance and the resultant shadowing or reverberations</li><li>• 50% of the time dependent on the imaging angle</li><li>• Direct relationship with the size of the foreign body</li><li>• Lower water content results in easier detection</li><li>• Entry Wound important for detection</li></ul>
Materials	<ul style="list-style-type: none"><li>• Difficult: Glass, Plastic Button</li><li>• Medium Easy: Shoelace, Shoe Sole, Cardboard, Coin</li><li>• Easy: Bullet, Bakelite, Leather, Ceramic, Brick, Dirt, Sand, Goose Dropping, Rock</li></ul>
Tissues	Skin > Muscle > Kidney > Heart > Liver > Spleen
Probes	L10-5 MHz > C4-2 MHz > P5-3 MHz
Examination	<ul style="list-style-type: none"><li>• Based on a thorough knowledge of anatomy</li><li>• Experience Matters</li></ul>

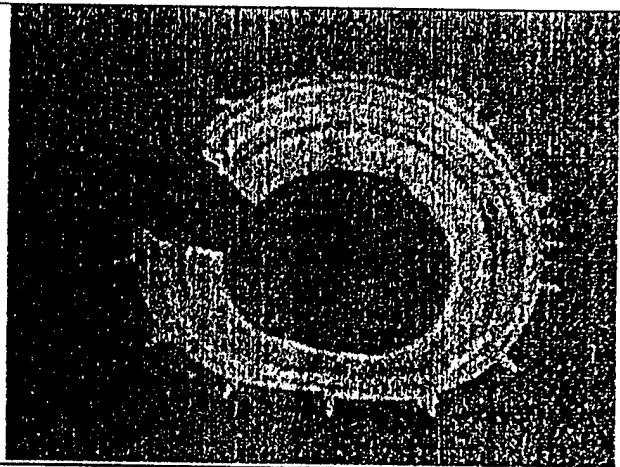
The method may provide a useful and practical clinical method for foreign body detection.



VS-50  
Antipersonnel

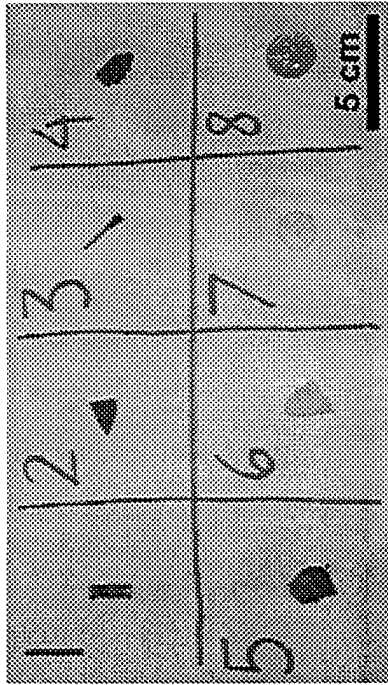


Top view of the screw on top of the VS-50 mine.

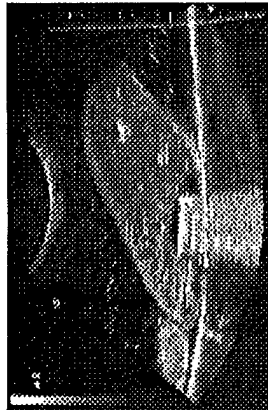


Bottom view of the piece of the mine. Note:  
threads  
for screwing this top piece into place.

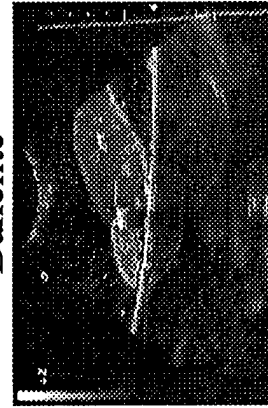
# MATERIALS



Bullet



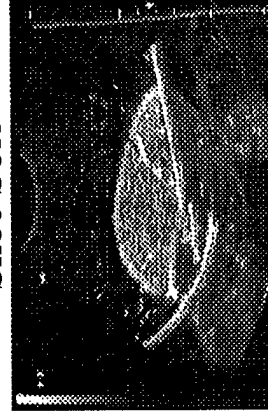
Bakelite



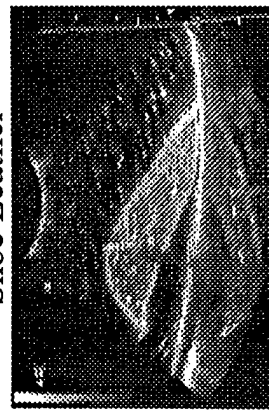
Shoelace



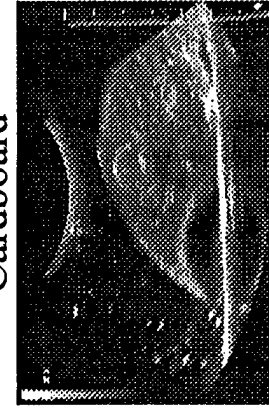
Shoe Sole



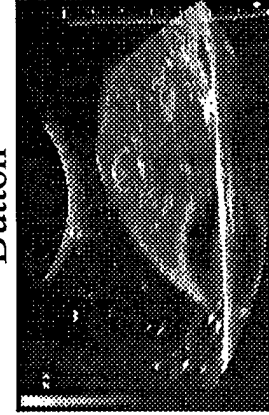
Shoe Leather



Cardboard



Button



Coin



**Interim progress report:  
Clinical study of Blunt Abdominal Trauma (BAT) patients  
using the HDI-3000 at Harborview Medical Center (HMC)**

F.A.Mann, Marla Paun, Jeff Olson,  
Sarah Shaves, Gayle Waitches,  
Bryan Goldman, Sam Sharar,  
Steve Carter, Roy Martin

**Establishment of clinical 'trauma environment' in which to trial the TRP portable US unit**

1. Implementation of BAT-TUS (transabdominal ultrasound):
  - 1.1. All BAT patients admitted to HMC Emergency Trauma Center (ETC) since 14.July:1997 who meet usual HMC-ETC criteria for diagnostic peritoneal lavage (DPL) have been randomized to receive either DPL or TUS. Worksheets (see attached) are completed by operator performing diagnostic procedure, returned to worksheet collection folder (n = 177 as of 9/8/97). Randomization performed prospectively by J. Olson using a 'sealed-envelope' system.
  - 1.2. All BAT-TUS are videotaped for subsequent re-review for examination adequacy (each zone graded on 5-point scale against criteria specified in SEE-US curriculum [see attached DPL & TUS data forms]) and accuracy by an HMC attending radiologist (FAM, SS, GW). Technical aspect of examinations are noted, including time to complete TUS, transducer(s) applied, use of 'flow' based imaging and appropriateness of depth and gain settings.

2. Preliminary results:

2.1 Tabular summary of BAT DPL vs TUS

	BAT	DPL	TUS
# patients	175 (152)	87 (64)	88
TP	20	9	11
TN	-	56	75
FP	-	0	2
FN	-	2	0
Accuracy	-	0.97	0.98
Sensitivity	-	0.82	1.00
Specificity	-	1.00	0.97
Substnd/incomplete	-	23	22
Substnd/incomplete	-	0.26	0.25

2.1.1 "Priveledged" populations:

Pregnant: TUS 4 patients, 1 showed hemoperitoneum  
Children: TUS 8 patients, all normal

**Establishment of clinical 'trauma environment' in which to trial the TRP portable US unit**

1. Implementation of BAT-TUS (transabdominal ultrasound):
  - 1.1. All BAT patients admitted to HMC Emergency Trauma Center (ETC) since 14.July:1997 who meet usual HMC-ETC criteria for diagnostic peritoneal lavage (DPL) have been randomized to receive either DPL or TUS. Worksheets are completed by operator performing diagnostic procedure, returned to worksheet collection folder (n = 415 as of 11/12/97). Randomization performed prospectively by J. Olson using a 'sealed-envelope' system.
  - 1.2 All BAT-TUS are videotaped for subsequent re-review for examination adequacy (each zone graded on 5-point scale against criteria specified in SEE-US curriculum ) and accuracy by an HMC attending radiologist (FAM, SS, GW). Technical aspect of examinations are noted, including adequacy of examination, time to complete TUS, transducer(s) applied, use of 'flow' imaging (Doppler, color Doppler or power Doppler) and appropriateness of depth and gain settings.

2. Preliminary results: Currently, 520 patients randomized. Discussion covers 415 cases acquired by 11/12/97.

2.1 Tabular summary of BAT DPL vs TUS

	BAT	DPL	TUS
# patients	415	209	206
TP	58 (14%)	34 (16%)	24 (12%)
TN	-	172	175
FP	-	0	5
FN	-	3	2
Accuracy	-	0.98	0.97
Sensitivity	-	0.98	0.92
Specificity	-	1.00	0.97
Substnd/incomplete	-	35	32
Substnd/incomplete	-	0.17	0.16
Non therapeutic laparotomy		0.53	0.44

**DPL/TUS Outcomes comparison data forms**

Case #: \_\_\_\_\_

**PATIENT HMC DATA LABEL**

**DPL:**

DPL technique:      Closed (percutaneous)      Open      Closed → Open

Technically -    Successful    Unsuccessful

Aspirated gross blood (>10cc):      Yes    No

Cell count "positive":      Yes    No

Cell counts:

RBC      \_\_\_\_\_

[Blunt > 100K RBC; Penetrating > 1K RBC]

WBC      \_\_\_\_\_

[Either Blunt or Penetrating > 500 WBC]

Bile:    Yes    No

Food particles:      Yes    No

Amylase:      \_\_\_\_\_

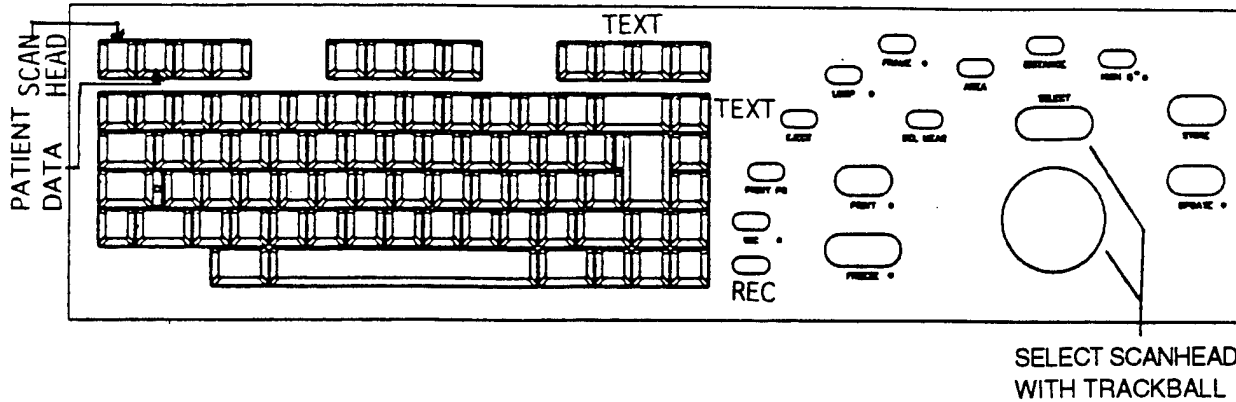
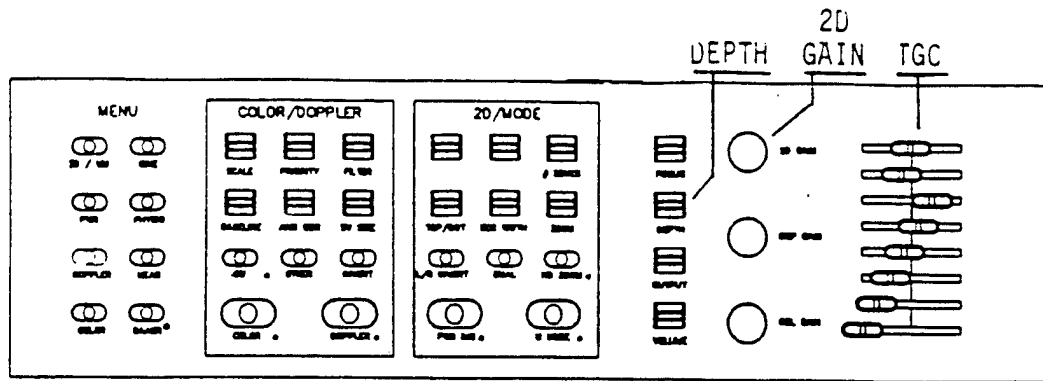
[> serum amylase]

Alk. Phosphatase:      \_\_\_\_\_

Operator: \_\_\_\_\_

R2    R3    R4    R5    Trauma Fellow    Attending Surgeon    Other: \_\_\_\_\_

POWER SWITCH  
ON THIS SIDE



## Knobology

1. **On/off** (Power switch) left hand side under the control panel and back panel adjacent to the cord.
2. **Patient data** Press the 'patient data' key at the left hand side of the keyboard, next to scanhead key.
  - 2.1 Select yes, Y on the keyboard.
  - 2.2 Enter patient's name.
  - 2.3 Hit tab. Enter patient's number.
  - 2.4 Select patient data key again to exit to scanning screen.

## 3. Scanhead selection

- 3.1 Press the 'scanhead' key on the left hand side of the keyboard.
- 3.2 Highlight desired scanhead with trackball and press 'select' button.
- 3.3 **P3-2 20mm** Greater depth penetration, less attenuation, poorer resolution, deep abdominal.
- 3.4 **C4-2 40mm** Curved array for abdominal work. Less penetration, more attenuation, better resolution, thinner patients.
- 3.5 Presets select General Abd. Highlight appropriate examination type and subtypes with trackball and press 'select' button.

P3-2 20mm



C4-2 40R



Tissue Specific Presets	
<ul style="list-style-type: none"> <li>◆ Abdomen</li> <li>◆ OB</li> <li>◆ Gyn/Fertility</li> <li>◆ Generic</li> </ul>	<ul style="list-style-type: none"> <li>◆ General Abd</li> <li>◆ Renal</li> <li>◆ Aorta</li> <li>◆ Transplant</li> </ul>

**4. Annotation** Text keys are located on the right hand side of the keyboard.

Text keys A through D are preset text. The single text key allows the operator to type in the text. The ATL HDI-3000 stationed in the HMC ER, Text key 'A' toggles through 'SAG' and 'TRANS', Text key 'D' toggles through the following sequence: PELVIS, R PARACOLIC, PERIHEPATIC, EPIGASTRIUM, PERISPLENIC, AND L PARACOLIC.

**5. Use plenty of gel.**

**6. Ultrasound exam design and strategy.**

Order of Search

1. Pelvis
2. Right paracolic gutter.
3. Perihepatic (Right upper quadrant).
4. Epigastric/pericardium.
5. Perisplenic. (Left upper quadrant).
6. Left paracolic gutter.

**7. Orientation of the transducer.**

The light or colored ridge on the transducer will determine the orientation. For a longitudinal scan the light/ridge should be pointed toward the patient's head. For a transverse scan the light/ridge should be rotated 90° and pointed to the patient's right side.

**8. Gain Controls**

**2 D Gain** Controls the overall amount of amplification or gain to the signals produced by the echoes returning from the body.

**TGC** Time gain control is the selective enhancement or diminution of the echoes returning from a specific depth. Equalize the echo texture throughout the organs so that the texture is homogeneous.

**9. Depth Control** Controls the depth range of the display. The maximum allowed depth is dependent upon the scanhead selected. The scale along the edge or the CRT-monitor is marked off in centimeters.



**10. Record the exam.** Rec button.

**11. What you must see.**

**1. Pelvis.** Midline just superior to the symphysis pubis. Transverse then longitudinal. Identify the urinary bladder. Perivesica spaces bilaterally. Vesicouterine and/or vesicorectal recesses, posterior bladder wall, mucosal signature gas or intraluminal.

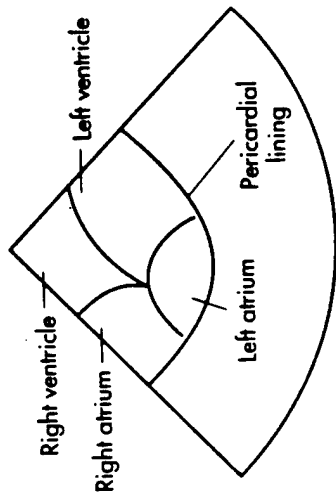
**2. Right and left Paracolic Gutter.** Transverse. See intraluminal gas or mucosal echo.

**3. Perihepatic.** Longitudinal, then transverse. Transducer position subcostal or in an intercostal position. Identify liver tip, subphrenic/perihepatic region. Identify the diaphragm. Depth set to keep the diaphragm within view. Locate the liver/kidney interface and Morrison's pouch.

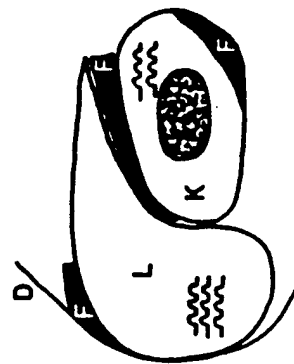
**4. Epigastric/Pericardium.** Transverse parallel to the long axis of the heart. Identify the left lobe of the liver. Subxiphoid, aim the transducer toward the left shoulder to view the heart. Identify the heart and the pericardium.

**5. Perisplenic.** Longitudinal, then transverse. Transducer in an intercostal position, near posterior axillary line. Identify the anteroinferior splenic tip. Locate the splenic/kidney interface. Identify the diaphragm. Depth set to keep the diaphragm in view. Locate the splenic flexure interface.

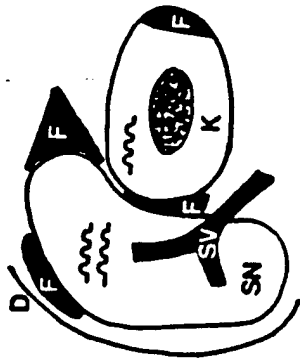
1. Sub Xiphoid Cardiac.



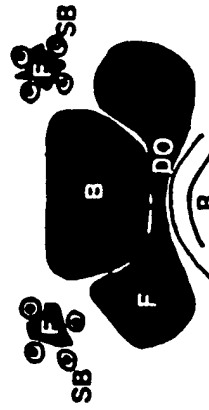
2. Right Upper Quadrant.



3. Left Upper Quadrant.



4. Pelvic.



F = free fluid; D = diaphragm; L = liver; K = kidney; SN = spleen; SV = splenic vein; B = bladder; DO = Douglas's pouch; R = rectum; SB = small bowel.

# Three Dimensional Model of the Peritoneal Cavity for Studying the Detection of Abdominal Free Fluid

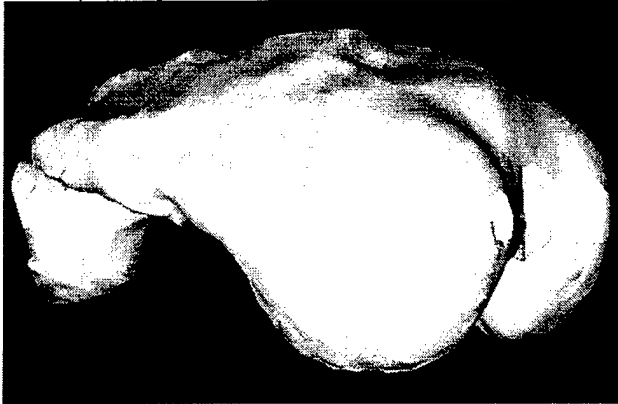
Shahram Vaezy Ph.D., Peter Nelson, Roy W. Martin, Ph.D, Steve Carter, M.D., Kevin Hinshaw, James F. Brinkley Ph.D. and Cornelius Rosse, M.D.

University of Washington, Seattle, WA

**Study Objective:** Ultrasonography is useful for detecting abdominal hemorrhage. An understanding of the abdominal fluid collection regions enhances this use. We are seeking to quantitatively describe this complex space.

**Methods:** The abdominal peritoneum was manually outlined in digital anatomic cross-sections obtained from the National Library of Medicine (via The Visible Human Project). Outlines were spatially assembled and three-dimensional (3D) reconstruction were produced using the "Skandha" software developed in the Department of Biological Structure, University of Washington.

**Results:** A representative 3D reconstruction is presented of the contour of the abdominal peritoneum with the subject: supine, head towards the right, and oblique to the observer. The two large lower lobular



excursions (center to right) are respectively, a cavity for the spleen/stomach and a cavity for the liver. The latter contains the Morison's pouch. The downward protrusion at the left contains the bladder and distally the Douglas' pouch.

**Conclusion:** The reconstruction illustrates the complex nature of the fluid collection "basin" and allows visualization of how fluid can migrate and be trapped in another region, secondary to postural change. We are currently adding the fluid dividing and distributing

channels to the model. We believe the model aids in understanding free fluid regional collection and how to detect it.

## **APPENDIX**

### **Telemetry Requirements**

#### **Clinical Hand-held Portable Ultrasound Unit**

##### **Mobile**

##### **Aircraft**

###### Military (Helicopter, Transport)

When bandwidth is available, 2-way audio + real-time video would be desirable. This would allow visualization of the video ultrasound (US) image for diagnostic purposes and would facilitate direction of the examination of the injured soldier. Video visualization of the injured soldier and scanhead position using a miniature video camera (CCD) would be an option.

When bandwidth does not allow real-time video, intermittent compressed video from a 'cine-loop' or slow scan video can be used.

When only low bandwidth is available, (e.g. 28.8 kHz telephone), selected static images with two-way audio can be used.

##### **Ship**

###### Military (Carrier, Surface, Submarine)

When bandwidth is available, 2-way audio + real-time video would be desirable. This would allow visualization of the video ultrasound (US) image for diagnostic purposes and would facilitate direction of the

examination of the patient. Video visualization of the sick or injured patient and scanhead position using a miniature video camera (CCD) would be an option.

When bandwidth does not allow real-time video, intermittent compressed video from a 'cine-loop' or slow scan video can be used.

When only low bandwidth is available, (e.g. 28.8 kHz telephone), selected static images with two-way audio can be used.

## **Vehicle**

### Military (HMMV, FAST)

When bandwidth is available, 2-way audio + real-time video would be desirable. This would allow visualization of the video ultrasound (US) image for diagnostic purposes and would facilitate direction of the examination of the injured soldier. Video visualization of the injured soldier and scanhead position using a miniature video camera (CCD) would be an option.

When bandwidth does not allow real-time video, intermittent compressed video from a 'cine-loop' or slow scan video can be used.

When only low bandwidth is available, (e.g. 28.8 kHz telephone), selected static images with two-way audio can be used.